

**A TECHNIQUE FOR THE MEASUREMENT
OF BLADE TIP CLEARANCE IN A
GAS TURBINE.**

A thesis submitted for the degree
of Doctor of Philosophy in the
University of London and for the
Diploma of membership
of Imperial College.

by

John William Hender Chivers

Department of Electrical Engineering
Imperial College
Exhibition Road
London
SW7 2BT

February 1989

ABSTRACT

This thesis is concerned with the development of a technique for the measurement of blade tip clearance for use in the production and optimisation of performance of aero gas turbines. Consideration is also given to possible future application of the technique in a closed loop turbine tip clearance control system on engines in passenger carrying service.

The operation and thermodynamics of a modern gas turbine are described and the relevance of compressor and turbine tip clearances is highlighted. The problems associated with obtaining such a measurement in a gas turbine environment are discussed and a measurement specification is derived which is applicable primarily to sea level bench engine testing.

Previously published and unpublished work in the field of gas turbine tip clearance measurements are reviewed. In the light of this information and the practical experience of the author in the field of turbomachinery instrumentation, a short list of potentially successful measurement techniques is derived. Optical, microwave, electromechanical, inductive and capacitive based measurement techniques are critically appraised against the measurement specification.

A capacitive based system is selected for further assessment in depth and is shown to be a particularly suitable technique in the context of a gas turbine compressor or turbine

operating environments. A novel capacitance transduction technique is proposed which uses a frequency modulated oscillator in combination with an active guarded electrode assembly. A clearance measuring system using this technique is designed and manufactured.

The performance of a prototype capacitance clearance system is evaluated in the laboratory against the derived specification. The system is then used on an engine compressor and finally on an engine turbine. The results from each of these tests are critically assessed and compared, where possible, with independent measurements and predictions derived from theoretical models of gas turbine structures.

It is concluded that the capacitive blade tip clearance measuring system performs as theoretically predicted and generally achieves the target measurement specification. Previously unobtainable measurements of transient blade tip clearance were obtained from an engine compressor and turbine by use of the measurement technique described. The thesis concludes by identifying aspects of the technique which would merit further research work in order to make it more suitable for future use in both research/development and production applications.

Except where reference is made to the work of others, the research and conclusions represented in this thesis are original as far as the author is aware.

ACKNOWLEDGEMENTS

I acknowledge with gratitude the assistance received from Rolls-Royce plc who have both funded the project and provided extensive facilities throughout its duration.

I would also like to thank both Mr. John Coplin (Rolls-Royce) and Dr. Colin Besant (Imperial College) who encouraged me to embark on this project and supported my application.

My two supervisors, Mr. R. J. "Jock" Hill, (Rolls-Royce) and Dr. Colin Vickery (Imperial College) deserve particular thanks for their guidance, advice and help in solving the many problems encountered during this research.

My sincere thanks are also given to my many colleagues at Rolls-Royce, particularly those past and present members of the Electronics and Measurement Techniques Department and the Instrument Department at Derby, who have assisted in bringing this project to a successful conclusion. Foremost in this category are Charlie Rickards and Bob Bish who were of great assistance in the development of a practical system. Also Bill Seaman and Bill Edmundson from Advanced Engineering who had sufficient faith in the technique to commit their project to its use and persistence to ensure a successful result. More recently David Foulds and Keith Stringfellow who are involved in improving and applying the measurement technique.

Special thanks are due to my wife Elisabeth for her encouragement and willing acceptance of a greater workload to enable me to devote the necessary effort to the research work and the production of this thesis. Finally, thanks are also due to my children, Jane, Matthew and Lucy who have helped in many ways to ensure this thesis was written.

TABLE OF CONTENTS

	Page
ABSTRACT	1
ACKNOWLEDGEMENTS	3
1.0 INTRODUCTION	9
1.1.0 Gas Turbine Principles	9
1.2.0 Problem Definition	16
1.3.0 Measurement Specification	19
1.3.1 Range	20
1.3.2 Accuracy	20
1.3.3 Environment	21
1.3.4 Dynamic Response	21
1.3.5 Output	22
1.3.6 Production System Requirements	23
1.4.0 Survey of Previous Work	24
1.4.1 Optical Triangulation	24
1.4.2 Electromechanical Probes	26
1.4.3 Fluidic Sensors	29
1.4.4 Capacitance Techniques	32
1.4.5 Optical Transmission	33
1.4.6 Magnetic Transducers	34
2.0 MEASUREMENT TECHNIQUE EVALUATION/SELECTION	37
2.1.0 Optical Triangulation	37
2.2.0 Optical Astigmatic	38
2.3.0 Microwave Reflectometer	40
2.4.0 Capacitance Technique	43

	Page
2.5.0 Final Selection	51
3.0 CAPACITIVE TRANSDUCTION TECHNIQUES	53
3.1.0 Capacitance Bridge	54
3.2.0 Constant Voltage Capacitance	56
3.3.0 Frequency Modulation	59
3.4.0 Environmental Factors	60
3.5.0 Guard Circuit Concept	62
3.6.0 Capacitance System Proposal	63
4.0 SYSTEM DESIGN CONSIDERATIONS	65
4.1.0 Measuring Probe - Sensor	66
4.1.1 Reactive Silver Braze	71
4.1.2 Silver Braze to Metallised Ceramic	72
4.1.3 Gold Braze to Metallised Ceramic	73
4.2.0 Measuring Probe - Modulator	75
4.2.1 The Oscillator	75
4.2.2 Oscillator Circuit Analysis	79
4.2.3 The Oscillator Regulator	91
4.2.4 The Guard Circuit Amplifier	93
4.2.5 Line Driver Amplifier	98
4.3.0 Ground Station	98
4.3.1 Frequency Demodulator	100
4.3.2 A.F.C. Control Amplifier	103
4.4.0 Calibration Factors	111
4.4.1 Blade Spacing Factor	112
4.4.2 Blade Stagger Angle Factor	118
5.0 PROTOTYPE SYSTEM DESIGN/MANUFACTURE	123
5.1.0 Measuring Probe	123
5.1.1 Measuring Probe- Sensor	124

	Page
5.1.2 Measuring Probe- Modulator	124
5.1.3 Measuring Probe- Assembly	128
5.2.0 Groundstation	135
5.3.0 System Interconnection Standards	140
5.3.1 Modulator/Demodulator Cables	141
5.3.2 Groundstation Rack Wiring	143
5.4.0 Data Processing and Display	143
5.5.0 System Error Analysis	145
5.5.1 Measuring Probe- Sensor/Modulator	147
5.5.2 Groundstation Demodulator	147
5.5.3 System Calibration	147
6.0 CLEARANCE SYSTEM EVALUATION: ENGINE COMPRESSOR	149
6.1.0 Introduction	149
6.2.0 Test Objectives	151
6.3.0 Probe Installation	152
6.4.0 Capacitance Probe Calibration	158
6.4.1 Calibration Equipment	158
6.4.2 Calibration Procedure	159
6.4.3 Probe Immersion Sensitivity	162
6.4.4 Probe Calibration Validation	168
6.5.0 Engine Test Programme	168
6.5.1 Surge-Prone Compressor	168
6.5.2 Surge-Free Compressor	172
6.6.0 Discussion of Results	173
6.6.1 Tip Clearance Probe Analysis	173
6.6.2 Test Results-Transient	175
6.6.3 Test Results-Dynamic	184

	Page
7.0 CLEARANCE SYSTEM EVALUATION: ENGINE TURBINE	190
7.1.0 Introduction	190
7.2.0 Turbine Blade Tip Geometry	193
7.3.0 Radial Clearance Probe Installation	197
7.4.0 Radial Clearance Probe Calibration	202
7.4.1 Calibration Equipment	202
7.4.2 Calibration Procedure	205
7.4.3 Probe Calibration Validation	207
7.5.0 Engine Test Programme	212
7.6.0 Discussion of Results	216
7.6.1 Transient Radial Clearance	216
7.6.2 Casing Eccentricity	219
8.0 CONCLUSIONS	223
8.1.0 Summary of the Research	223
8.2.0 Proposals for Further Work	226
8.2.1 Guard Circuit Amplifier	226
8.2.2 System Calibration	226
8.2.3 Measuring Probe-Sensor	227
9.0 REFERENCES	228

1.0 INTRODUCTION.

1.1.0 Gas Turbine Principles.

The development of the gas turbine engine as an aircraft powerplant has only been in progress for the last 50 years. Frank Whittle was granted his first patent for a gas turbine which developed a propulsive jet in 1930. However eleven years were to elapse before his original engine completed its first flight and this engine formed the basis for the modern gas turbine.

The gas turbine is basically a heat engine which utilises air as the working fluid to generate thrust. The thermodynamic working cycle on which the gas turbine functions is shown in its most basic form in Figure 1.1 and can be compared readily with the better known four stroke piston engine. Figure 1.2 compares pictorially the working cycles of a gas turbine and a piston engine.

Both engine cycles involve induction, compression, combustion and exhaust; the two major differences being that in the gas turbine combustion occurs at nearly constant pressure (c.f. constant volume in the piston engine). Also the cycle is continuous in a gas turbine (c.f. an intermittent cycle in the piston engine). This is achieved by the use of separate components to achieve the specific functions. Figure 1.3 demonstrates clearly how gas pressure, temperature and velocity vary through a simple single spool axial flow gas turbine.

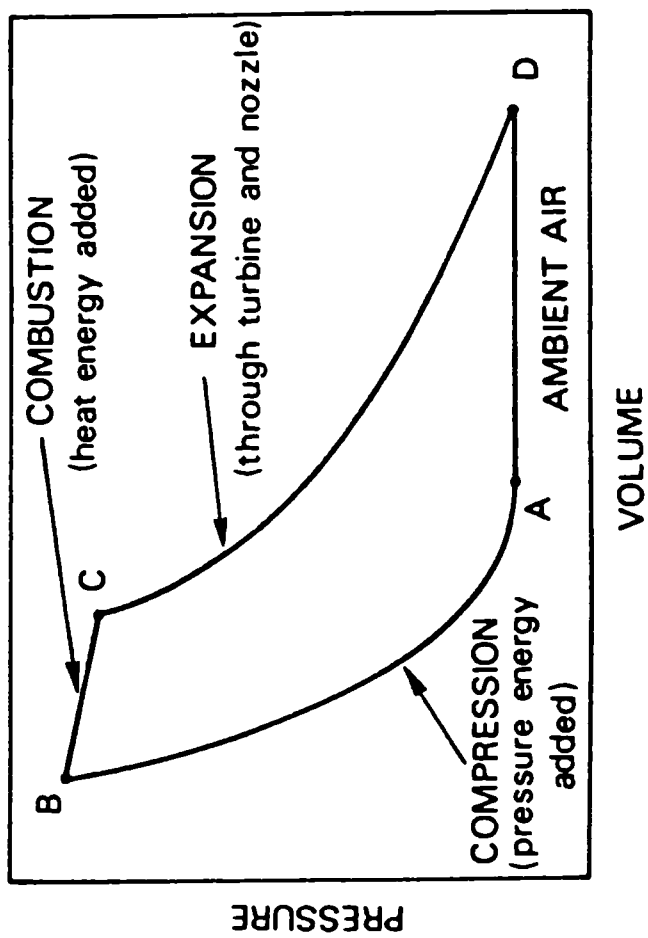


Figure 1.1 The Working Cycle on a Pressure Volume Diagram of a Gas Turbine.

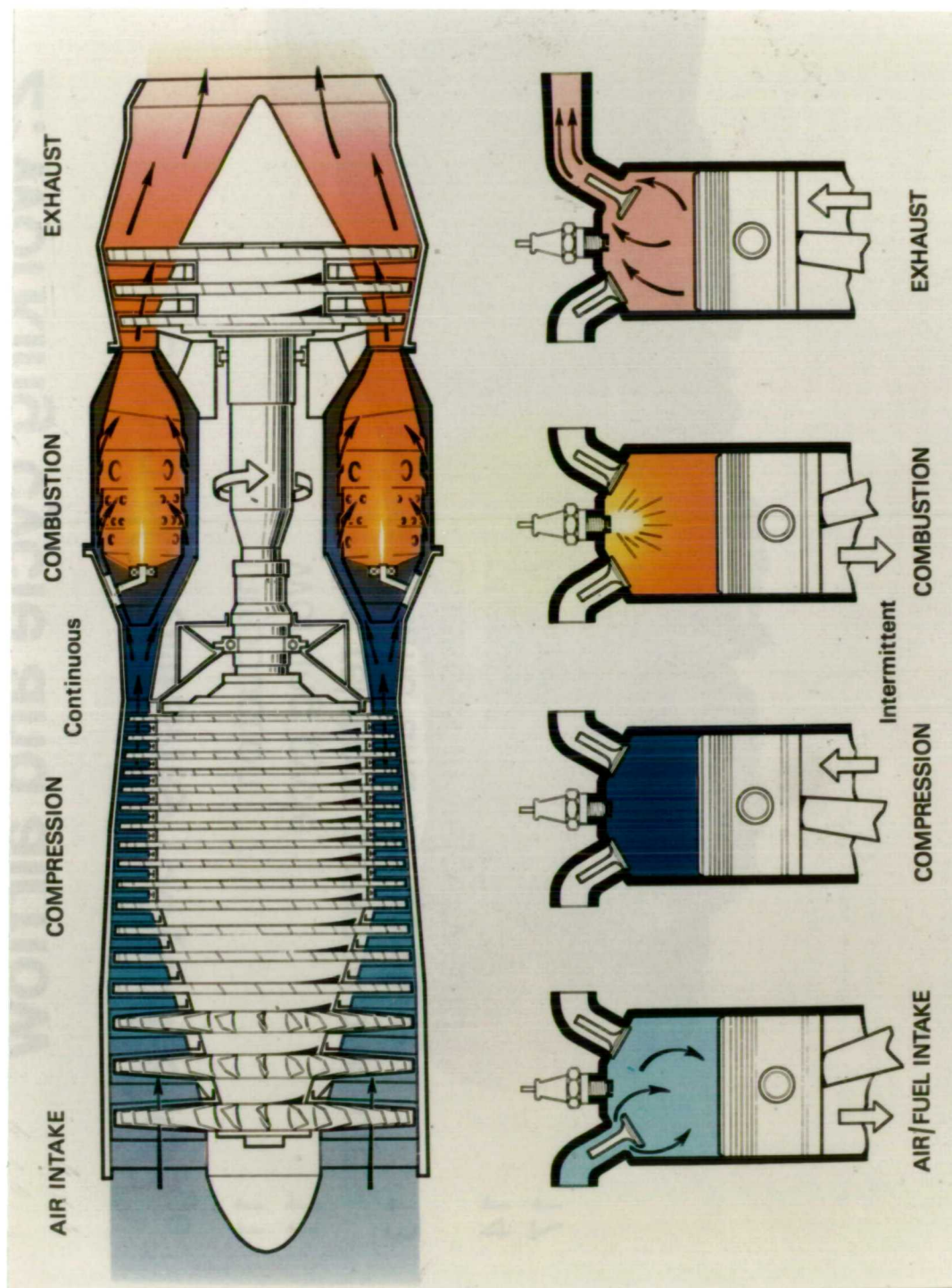


Figure 1.2 A Comparison Between The Working Cycle of a Turbo-Jet Engine and a Piston Engine.

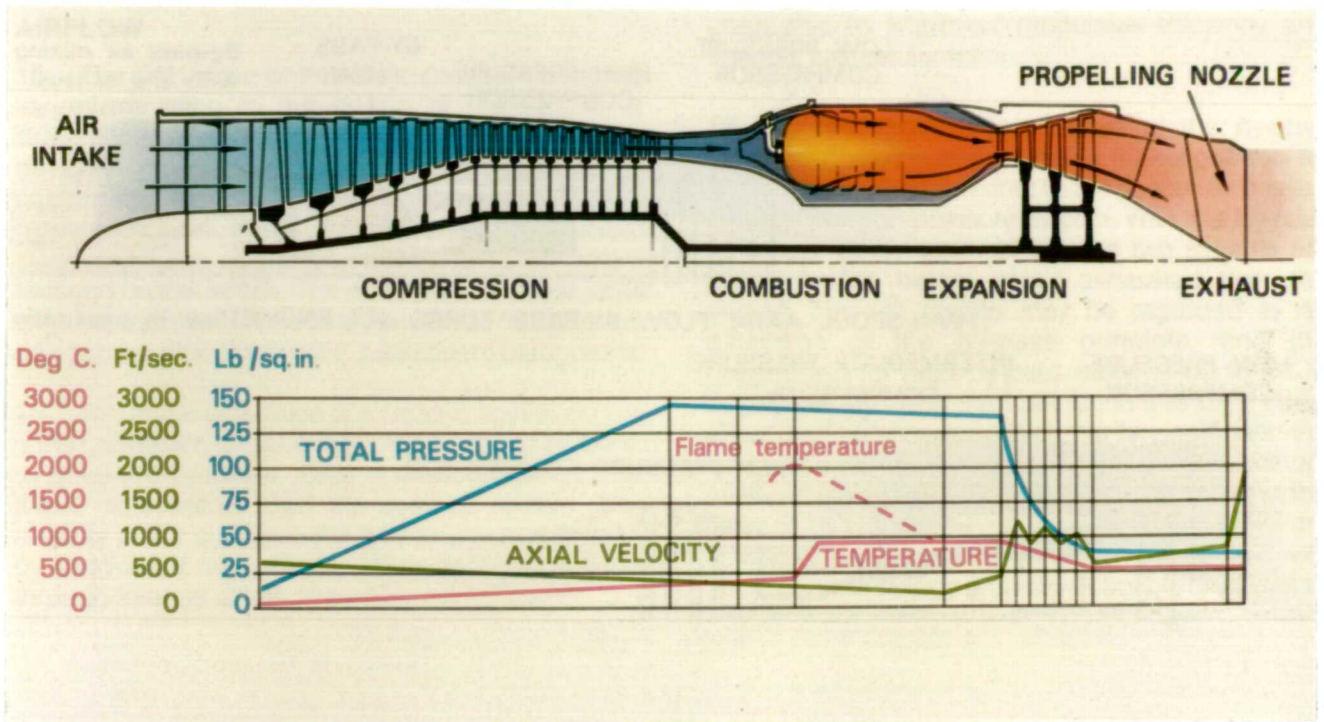


Figure 1.3 Gas Pressure / Velocity / Temperature Relationships.

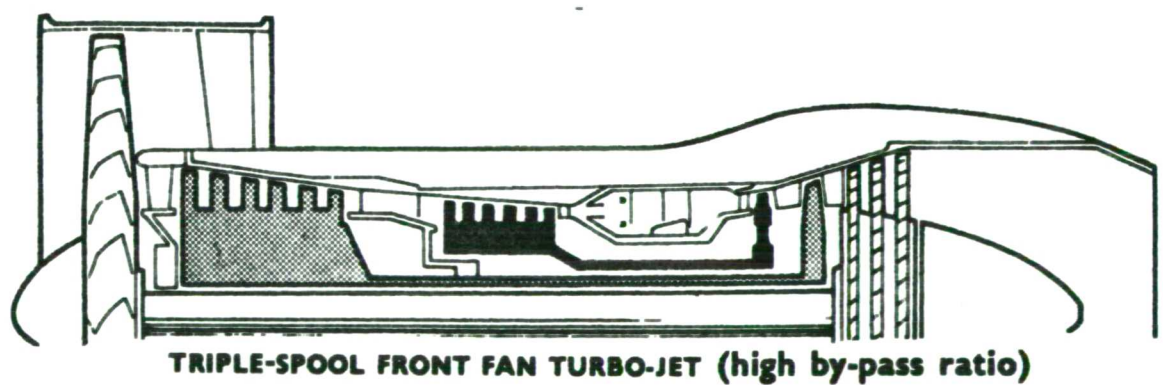


Figure 1.4 Mechanical Arrangement of a Gas Turbine Engine.

Compression of the air in a modern gas turbine is most usually achieved by means of an axial flow type of compressor (c.f. the older centrifugal design of compressor). The compressor may consist of one or more totally independent rotor assemblies. The Rolls-Royce RB211 family of large civil turbofan engines have three compressor assemblies, the Low pressure (LP), Intermediate pressure (IP) and High pressure (HP) compressors as shown in Figure 1.4. Each compressor is driven by its own turbine at an optimum speed which is governed solely by the air flowing through the engine: the only coupling between the three spools is that provided by the airflow. The use of three compressors in series enables a higher overall pressure ratio to be achieved with a greater operating flexibility than if a single compressor were used. A sectioned view of a typical triple-spool compressor is shown in Figure 1.5.

The LP compressor (the Fan) consists of just one rotor stage and, in the case of the RB211, generates approximately 80% of the engine thrust. The IP and HP compressors are multistage units, each stage consisting of a row of rotating aerofoil section blades followed by a row of aerofoil stator vanes.

From the front to the rear of each compressor i.e. from the low to the high pressure end, there is a gradual reduction of the air annulus area between the rotor shaft and stator casing. This is necessary in order to keep the axial air velocity at a roughly constant value as the air density increases through the compressor. Figure 1.6 shows the pressure/velocity changes diagrammatically.

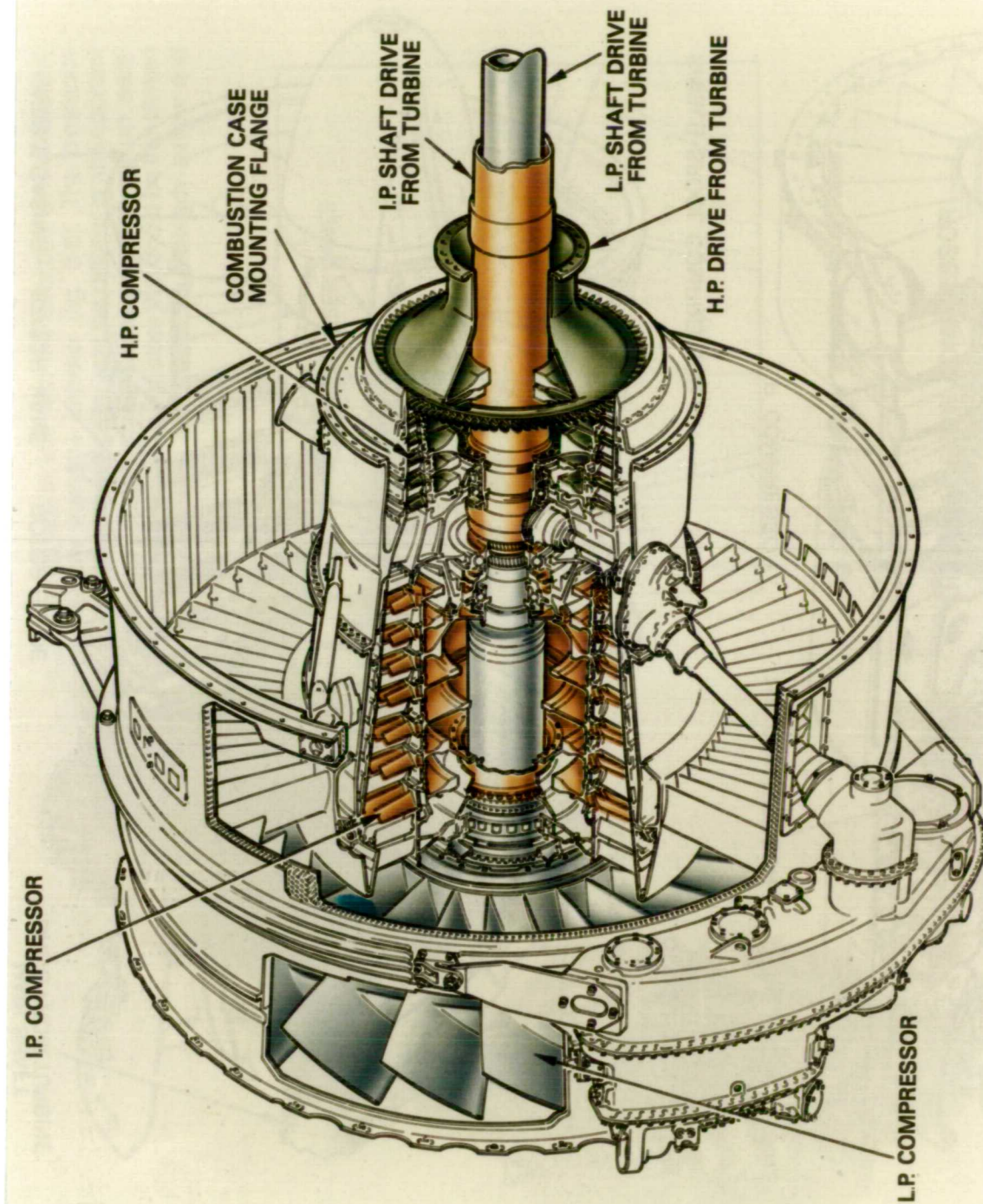


Figure 1.5 Typical Triple-Spool Compressor.

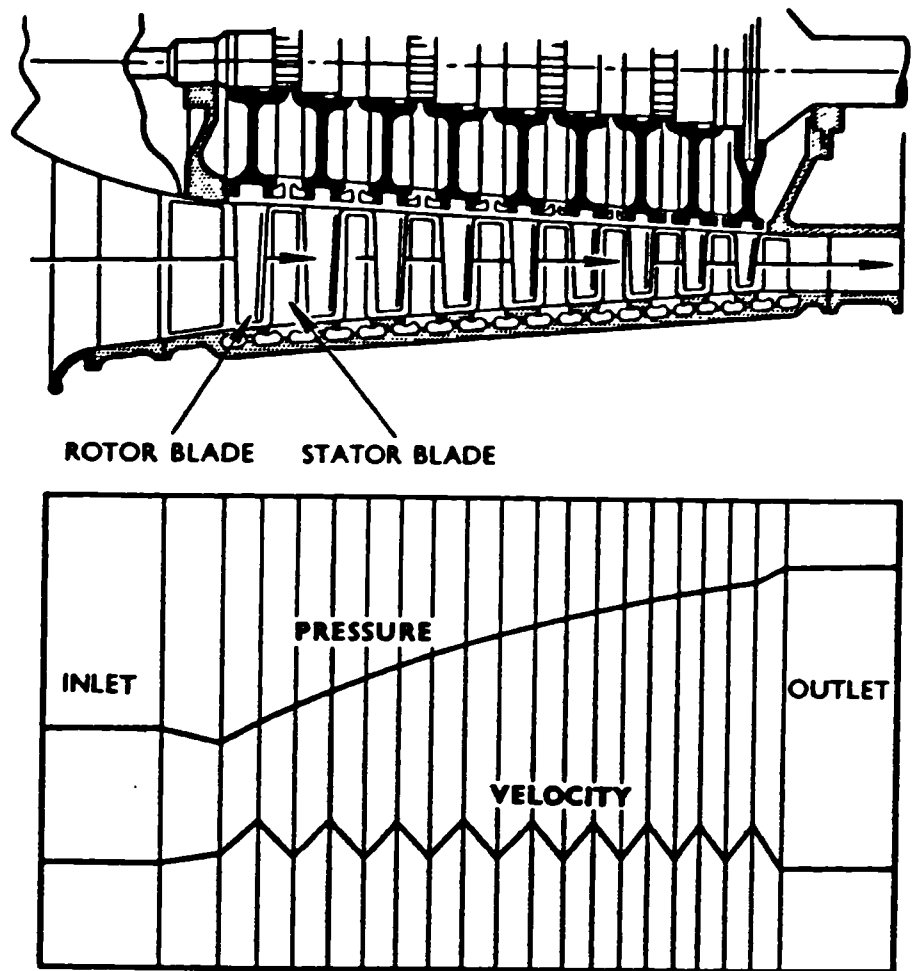


Figure 1.6 Pressure & Velocity Changes Through an Axial Compressor.

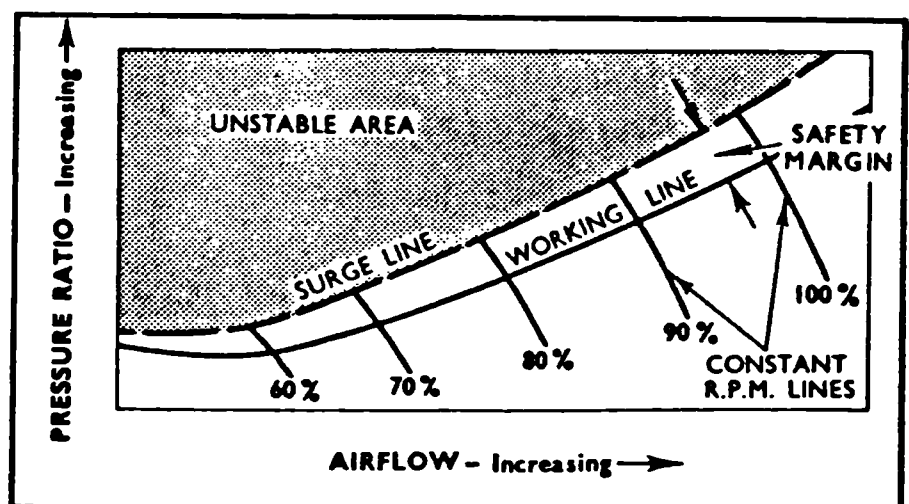


Figure 1.7 Limits of Stable Airflow in a Compressor.

1.2.0 Problem Definition.

In both compressors and turbines the aerofoil section blades rotate in very close proximity to the stationary casings. The clearance which exists between the tips of these rotor blades and the casings is typically some 2% of blade height. For example at the inlet and outlet of the HP Compressor of a modern gas turbine, the rotor blades would have heights of 125 millimeters and 50 millimeters giving nominal running clearances of 2.5 millimeters and 1.0 millimeters respectively. During normal engine operation in a flight environment, these clearances can vary from 0% to 4% of blade height. These small clearances have a profound effect on the design of compressors, turbines and entire engines.

Compressor blades are designed to generate a specific pressure rise and air velocity increase over the engine speed range. Any phenomenon which disturbs the pressure/ velocity/ rotational speed relationship may cause the airflow across the blade to break away and create eddies until eventually the blade stalls. When a sufficient number of stages in a multi-stage compressor reach a stalled condition the compressor will surge. A plot of Compressor Pressure Ratio against Airflow for a variety of constant rotational speed lines is a convenient way of summarising the performance of a compressor. Figure 1.7 shows diagrammatically such a plot which defines the limit of stable airflow in a compressor.

The "working line" is set as part of the cycle and component

matching of the engine. A compressor is designed to have a surge pressure ratio which allows a margin to accommodate changes in the working line during transients, and change of compressor surge pressure ratio due to transient change of tip clearance or deterioration within the compressor.

The value of pressure ratio and airflow at which surge occurs is known as the "surge point". This point is a characteristic of each compressor speed and a line which joins all the surge points together is called the "surge line" and represents the boundary between stable and unstable compressor operation. Maximum compressor efficiency occurs just before the surge point is reached. In practice, compressors are designed to have a safety margin so that surge conditions are avoided at all times and the "Working Line" expresses the usable compressor operating characteristics as opposed to the "Surge Line".

Thus the main effects of large blade tip clearances on a gas turbine are:-

1. Reduced efficiency. Air can leak back over the tips of the rotor blades.
2. Reduced compressor surge margin. For a given rotational speed and airflow, increased tip clearance has the effect of reducing the pressure ratio and the surge line approaches the working line.
3. Reduced gas flow through the engine.

Typically for a modern large gas turbine, an increase in tip

clearance of 0.125 millimeters in the HP compressor can reduce compressor efficiency by 0.5% and increase the specific fuel consumption (s.f.c.) of the engine by 0.2%. In the case of the HP turbine a similar increase in tip clearance decreases the turbine efficiency by 0.5% and increases s.f.c. by 0.25%. Freeman's paper (Ref.1) which is concerned with the effects of tip clearances in axial turbomachines, attempts to both identify the results of changes in tip clearances and list the causes. The factors identified as contributing to the tip clearances are:-

1. Production tolerances.
2. Rotor centrifugal growth.
3. Rotor thermal growth.
4. Stator and casing thermal growth.
5. Stator casing gas loads.
6. Rotor blade deflections.
7. Thrust loads.
8. Accelerations.
9. Asymmetries.
10. Wear of blade tips and seals.

Stated simply: the changes in casing diameters are caused primarily by thermal effects and the changes in rotor diameters are primarily centrifugal (C.F.) growth and thermal growth. A time delay is associated with each of these changes for any change in engine operating condition. The growth of the rotor due to C.F. tracks rotational speed and is thus virtually instantaneous. The thermal growth of the casings is fairly rapid as the structural mass is low, thus having a

small thermal inertia. The rotor thermal growth is considerably slower because the mass, and hence the thermal inertia, is relatively large, and also the rotor discs, in which the blades are retained, are insulated from the hot gas path.

To summarise: it can be seen from the preceding discussion that variations in the operating tip clearances of a gas turbine can have a very powerful effect on the very viability of an engine in the current highly competitive marketplace. Considerable time and effort is spent in attempting to minimise the tip clearance variations by the use of such techniques as thermal matching of rotors to casings, isolating stator casings from thrust loads, etc. As part of the engine development process it is essential that measurements of actual tip clearances are obtained throughout the engine to either confirm predicted behaviour or, where necessary, to modify and develop the engine structural model being used.

The measurement requirement can be stated quite simply. It is to provide a blade tip clearance measuring system which can be integrated with the routine suite of instrumentation techniques used during the rig testing of research compressors and turbines and during the development phase of complete engines on sea-level test beds. This thesis is concerned with the development of a system to fulfil the above requirement.

1.3.0 Measurement Specification.

1.3.1 Range.

Blade tip to casing design clearances are typically some 2% of blade height, a figure which is limited by the magnitude of casing distortions and mechanical integrity considerations. For a modern large gas turbine in the thrust range 250 to 400kN, turbine and compressor blade to casing tip clearances of between 0 and 2.5 millimeters must be measured. In order to ensure that no damage is caused to a tip clearance measuring system whenever a blade tip to casing rub occurs, it is essential to install the sensor underflush of the casing lining, typically by 0.5mm. Taking into account this measuring system standoff for reasons of sensor integrity, the required measuring range is 0.5mm to 3.0mm. A measure of the average clearance of all the blades in a rotor stage from a fixed circumferential position on a casing is of most use to both the Research and Development Engineer. The measurement of individual blade clearances is not considered to be an essential system requirement. This is due to the fact that in all rotor stages in a gas turbine, the blades are manufactured to have a very tight tolerance on height. Additionally for high pressure blading it is not unusual for the blades in a fully assembled rotor to be machined to a uniform length by grinding the blade tips prior to engine build.

1.3.2 Accuracy.

A system total error band of plus and minus 5% of reading down to a minimum reading of 0.5mm under all environmental conditions is a requirement of the Technology and Research

Areas. This accuracy can be expressed in terms of either component efficiency or engine specific fuel consumption (sfc). For example, at the design clearance values for the last stages of a high pressure compressor or a high pressure turbine, the 5% of reading tip clearance error band is equivalent to a component efficiency error band of 0.3% or an sfc uncertainty of 0.1%.

1.3.3 Environment.

As the air passes through a gas turbine the maximum gas pressures and temperatures between the blade tips and the casings ie in the measuring gap, typically vary as shown in the following table:-

	Temperature	Pressure
Engine Inlet	288K	100kPa
H.P.Compressor Delivery	809K	2.76MPa
H.P.Turbine Inlet	1500K	2.60MPa

The environment adjacent to the engine core casings under the fairings are typically ambient pressures and zone air temperatures of 450K above the compressors rising to 500K above the turbines.

1.3.4 Dynamic Response.

Blade passing frequencies of up to 20kHz are typical in both compressors and turbines of a modern large gas turbine with

rotational speeds of up to 10000 RPM and 100 plus blades per stage. A blade to space ratio in the order of 1 to 10 is usual for a compressor, which implies that a tip clearance measuring system requires a bandwidth in the region of 2 MHz. Blades in a turbine generally have a thicker chord in order to contain the air cooling passages. Thus the effective blade/space ratio is less than the compressor blade/space ratio by a factor of two so reducing the required system bandwidth by the same factor. The actual spatial resolution of any sensor used to detect the blade tips will have a powerful effect on the clearance system bandwidth requirements.

Although the system bandwidth is relatively high due to the intermittent presence of the blade tips in front of the measuring probe, the rate at which the average blade tip clearances vary is low. Maximum rate of change of clearance occurs during an engine slam acceleration (where the engine throttle is moved as rapidly as possible from idle to take-off power setting) or deceleration, generating possibly as much as a 50% change in measured clearance in 3 to 4 seconds.

1.3.5 Output.

An analogue voltage is required of average blade tip clearance. The level is not critical but should be in excess of 1 volt with a source impedance of less than 10 ohms to enable the system to drive all recording/display devices without buffer amplifiers. A linear relationship of voltage to clearance is desirable but is not considered essential.

1.3.6 Production System Requirements.

In order to satisfy the requirements of a measuring system for use in a highly critical passenger carrying application, additional requirements must be fulfilled. Although consideration of these requirements is not the subject of this thesis, factors such as fail safe operation, target reliabilities of 1 system failure in 100,000 hours of operation, overhaul periods of 5000 hours and the requirement that the measurement process must not affect the engine efficiency, were kept in mind throughout the measurement technique selection and development.

1.4.0 Survey of Previous Work.

Over the last 10 to 15 years the U.S.A. appears to have been the country most active in the research of new techniques for the measurement of gas turbine blade tip to casing clearances. One technique, the optical triangulation, is conspicuous by the number of different teams of researchers who have investigated and developed its application to gas turbines.

1.4.1 Optical Triangulation.

The optical triangulation measurement technique has been referred to under various headings such as a "laser proximity probe", "laser triangulation probe" or "laser optical clearance system". The technique has been investigated at Pratt and Whitney Aircraft by Drinkuth, Alwang and House (Ref.2), Ford (Ref.3), Barranger and Ford (Ref.4) and Hardy (Ref.5); at Avco Lycoming by White (Ref.6) and at General Electric by Baker, Grady and Mauch (Ref.7).

In all the work referred to above, a point source of light is transmitted to an engine mounted probe via an optical fibre. With reference to Figure 1.8, this intense spot of light is focussed by means of the input lens onto the turbine blade tips at position "A". Almost exclusively a Helium-Neon laser is used as the light source, not for the coherent properties of the light, but simply because the illumination is intense, has a small spot size and is well collimated. The projected spot of light on the turbine blade tips, "A", is imaged out of the engine via the output lens onto a light spot position

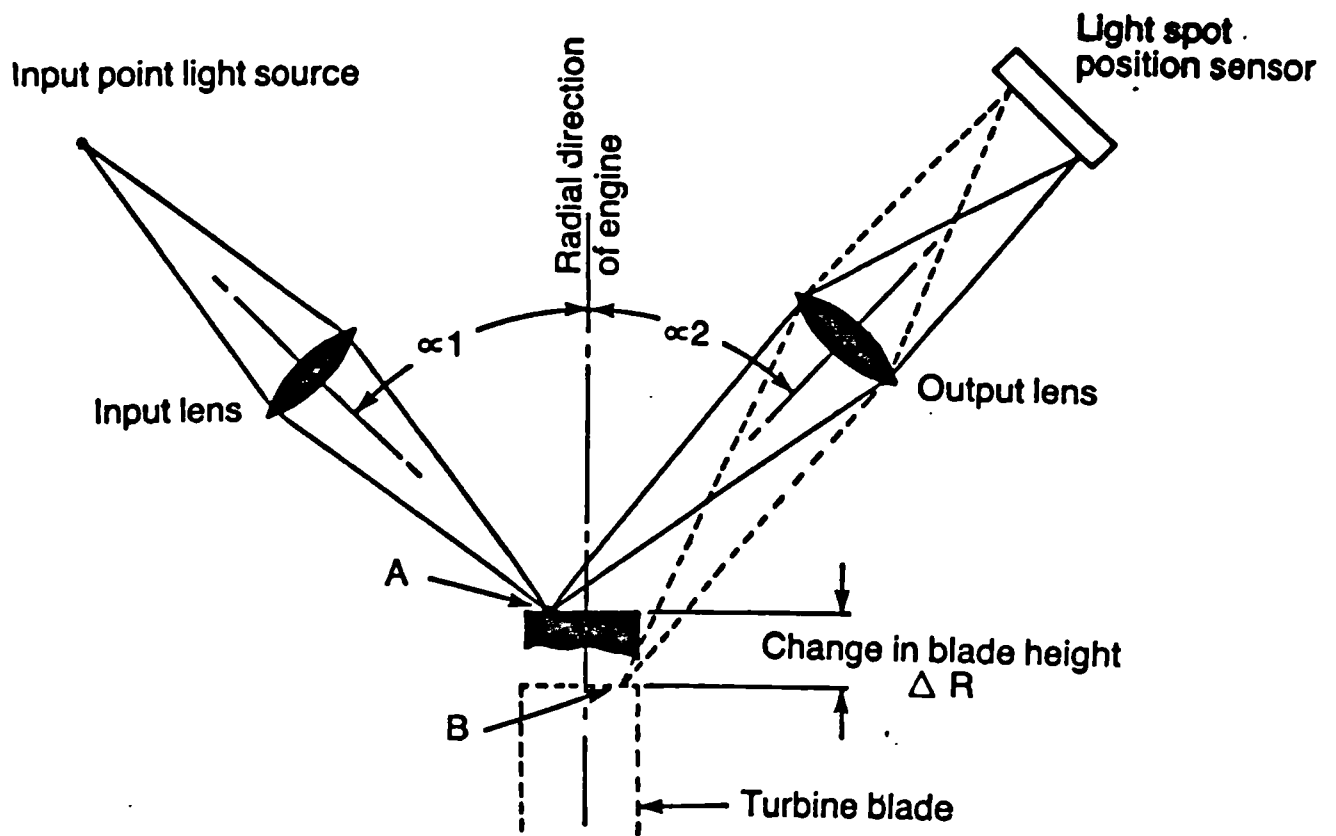


Figure 1.8 Optical Triangulation Clearance Probe
- Principle of Operation.

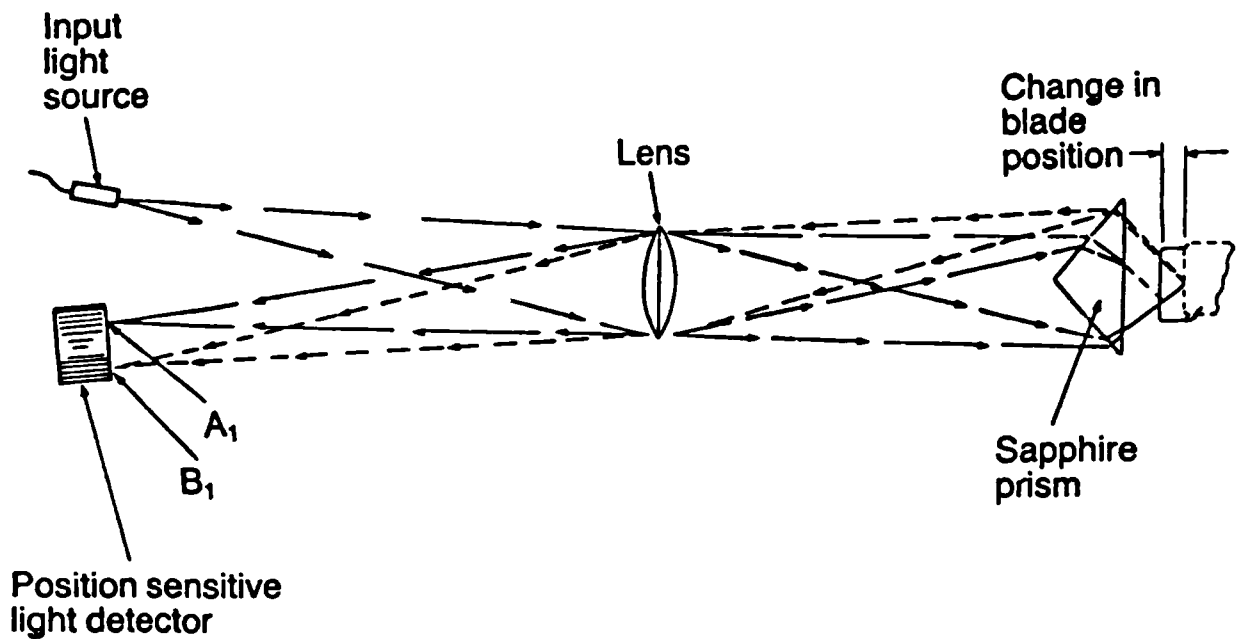


Figure 1.9 Folded Optical Triangulation Probe.

sensor or via a coherent fibre optic bundle onto a television vidicon tube. As the turbine blades move radially inward by an amount ΔR , the position of the projected light spot on the turbine blade tip moves from position "A" to position "B". This movement of the light spot on the blade tips results in a linear movement of the image on either the position sensor or the vidicon tube which can then be quantified. By use of a suitable calibration factor, the movement ΔR can be measured. A schematic diagram of a more practical embodiment of the triangulation principle is shown in Figure 1.9. This arrangement requires only one access hole through the engine casings and provides a considerably more stable measurement than that derived from a separate transmitter/receiver optical system.

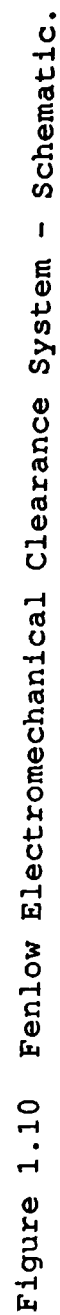
1.4.2 Electromechanical Probes.

The first commercially available clearance measuring system which could be used to continuously monitor blade tip clearances in turbomachinery research and development appeared in the early 1950s. It was manufactured by a U.K. company, Fenlow Ltd. The "Fenlow" probe, as it not surprisingly became known, is based on an electromechanical arrangement to measure the displacement of an electrically grounded target. The probe consists of an a.c. repeater motor which is used to slowly move an insulated wire towards an earthed target i.e. a turbine blade tip. The repeater motor is electrically driven by a remote transmitter which in turn is mechanically driven by a dc motor. A schematic diagram of the Fenlow clearance system is shown in Figure 1.10.

In operation, the wire which is traversed by the repeater motor, is electrically charged via a resistor/capacitor integrator circuit to a potential of approximately 600 volts. The separation between the end of the wire and the blade tip decreases as the wire is driven towards the blade until the gap is sufficiently small (generally less than 0.025mm) so that a spark jumps the gap and the capacitor is discharged. The wire is now at or near to ground potential, a condition which is determined by the probe voltage level detector. Under these conditions, the direction of rotation of the repeater motor is reversed and the wire is retracted from the blade. After some 300 milliseconds, the capacitor has recharged and the potential on the wire risen to such a level that the direction of the repeater motor is once again reversed and the wire moves towards the target.

Thus in operation the wire oscillates above the target with an amplitude of approximately 0.03mm. A measure of the displacement is achieved by connecting a mechanical turns counter to the dc motor. The gearing of the system is such that one complete revolution of the dc motor causes a linear displacement of the probe wire of exactly one thousandth of an inch. In this manner the turns counter indicates displacement directly in thousandths of an inch.

In the last 5 years this obsolescent technique has been given a new lease of life by the incorporation of new technology, first by Amsbury and Chivers (Ref.8) and later by Davidson (Ref.9).



In the updated Electromechanical Clearance System the repeater motor is exchanged for a digital stepper motor, the dc motor and transmitter are eliminated and a microprocessor controlled drive and measure system substituted for the thermionic valves and relay logic.

Work by Knoll, Schedl and Kappler (Ref.10) at MTU in Germany has been directed at the development of a remarkably similar electromechanical clearance system (the EMAG) to that described by Davidson (Ref.9).

However all these electromechanical based measurement techniques suffer similar disadvantages when operated in a gas turbine environment. These are:-

1. Unreliability of the mechanical actuators in high vibration/high temperature environments.
 2. Complex, heavy and expensive measuring probes.
 3. Susceptibility of probes to damage due to intermittent contact with blade tips under vibratory conditions of casings/probes or eccentricity/orbiting of the rotor.
 4. Indication only of clearance to the longest blade.
- Information on average or individual blade clearances is not available.

1.4.3 Fluidic Sensors.

A fluidic based displacement measurement technique has been identified and has found particular popularity in the power generation industry. This is due primarily to the technique

being totally immune to magnetic or electrical disturbances which are occasionally present in large power generators due to d.c. unipolar effects. Belsterling (Ref.11) comprehensively reviews a range of pneumatic back-pressure sensors and nozzle designs which have been developed and evaluated. Hall and Jones (Ref.12) concentrate their efforts on one particular design, referred to as a "cone-jet" sensor, using air as the working fluid as compared with the earlier work of Rubinshtein and Trubilov (Ref.13) which uses steam as the working fluid. The particular air gauge described by Hall and Jones, shown diagrammatically in Figure 1.11, is typical in that air from a constant pressure supply is directed into a conical jet through a nozzle. If the sensor is positioned normal to a plane surface and is sufficiently close for the surface to truncate the air flow cone, the pressure inside the cone will rise. This is detected and measured by means of the static pressure tapping arranged on the axis of the probe. A typical relationship between the probe to surface clearance and a non-dimensionalised back pressure is shown in Figure 1.12. However, experiments have been conducted in the U.K. using such an air jet technique to observe turbomachinery blade tips. Although the test data is not currently available in the public domain, two severe problems, specific to the particular application, have emerged. These are:-

1. The effective area of the target (the blade tips) presented to the jet of air is almost an order of magnitude less than the target area of a continuous surface e.g. a shaft or rotor disc. This small effective area results in a very weak measured back pressure versus

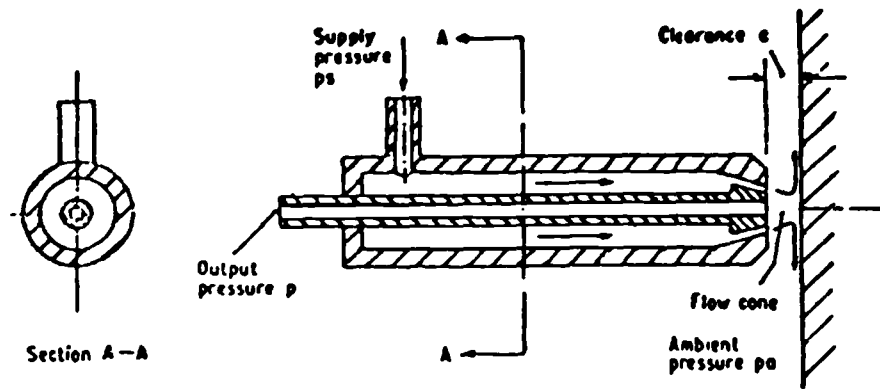


Figure 1.11 Fluidic Cone - Jet Sensor

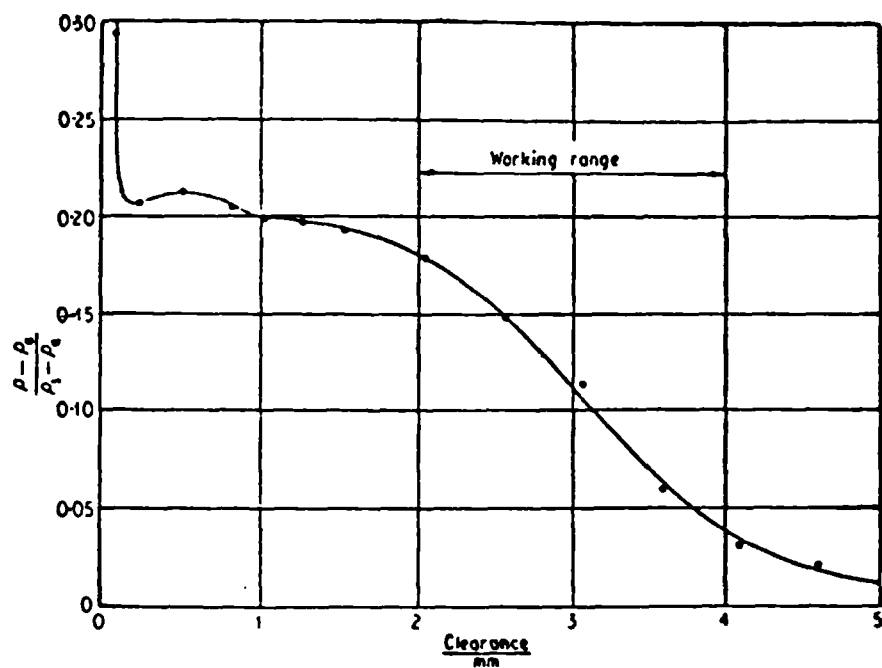


Figure 1.12 Typical Calibration Curve for Cone - Jet Sensor.

clearance relationship.

2. The back pressure /clearance relationship is affected by the Mach number of the gas passing across the measuring nozzle.

The cone-jet sensor initially appears very attractive due to its extended measuring range (when compared with the basic back pressure system), its relative simplicity and potential robustness. Unfortunately the above two problems effectively eliminate the technique as a viable gas turbine blade tip clearance measuring system.

1.4.4 Capacitance Techniques.

Various blade tip clearance measuring systems which rely on the measurement of the electrical capacitance formed between a casing mounted insulated electrode and the rotor blade tips have been identified. Barranger at N.A.S.A. Lewis (Ref.14) describes improvements to a system in which the blade tip to electrode capacitance forms an element in a resonant LCR (inductance, capacitance and resistance) circuit. The inductive component of the resonant circuit is link coupled via a 50 ohm impedance transmission line to a remote oscillator circuit. The oscillator output frequency is a function of the measured capacitance and hence the blade tip clearance. However the oscillator frequency is also a function of the temperature of the resonant circuit in the measuring probe and the temperature of the probe tip. The capacitance to be measured between an electrode and a

blade tip is typically 1 to 10 picofarads. This capacitance, however, is shunted by the total capacitance of the probe and connecting cable which may be two orders of magnitude greater than the clearance related capacitance. Even relatively small temperature induced changes in the standing capacitance of the probe/cable will thus cause errors in the measurement which are many times greater than the distance related capacitance. The system improvement which Barranger describes consists of switching a known complex impedance in parallel with the probe tuning elements whenever the system has stabilised at an operating temperature. The effect this has on the measurement is observed and a correction factor for temperature induced errors is derived. Knoll (Ref.10) in addition to covering the EMAG electromechanical system, describes a d.c. polarised capacitance system referred to as a "Coulomb-Probe". This system makes use of a guard electrode arrangement, similar in effect to that described by Amsbury and Chivers (Ref.8) in order to minimise temperature induced changes in capacitance of the probe and cable and hence the errors in the measurement of tip clearance.

1.4.5 Optical Transmission.

A simple optical based technique has been investigated by Poppel at NASA, Lewis (Ref.15). The prime purpose of the work package was to identify the technology base required to develop a compressor tip clearance measuring technique which would provide an input to a digital electronic

engine control system. The proposed optical arrangement is shown schematically in Figure 1.13. Essentially light is transmitted through the rotor blade to casing gap. Timing measurements of the exact instant when each rotor blade blocks and unblocks the light beam can be related to the absolute clearance, providing account is taken of rotor speed, rotor blade tip diameter and the angle between the blades.

The work showed that the measurement technique, although having a very limited range (less than 0.5mm), would appear feasible in a compressor environment. However the instability of such a long optical path length (approximately 150mm) in a turbine environment due to refractive index variations caused by extreme gas temperature and density gradients would render the technique unusable.

1.4.6 Magnetic Transducers.

The last and most recent tip clearance measuring technique identified has been proposed by Besant and Wright of Imperial College (Ref.16). The system uses a simple high temperature casing mounted magnetic transducer which generates an electrical signal as a result of the rapid passage of turbine blade tips through the magnetic field of the transducer. In order to increase the probe output to a usable level, slugs of a high permeability material, such as Permendur, are brazed into the blade tips. By ensuring that one such slug in a rotor is at a known different radius from all the other

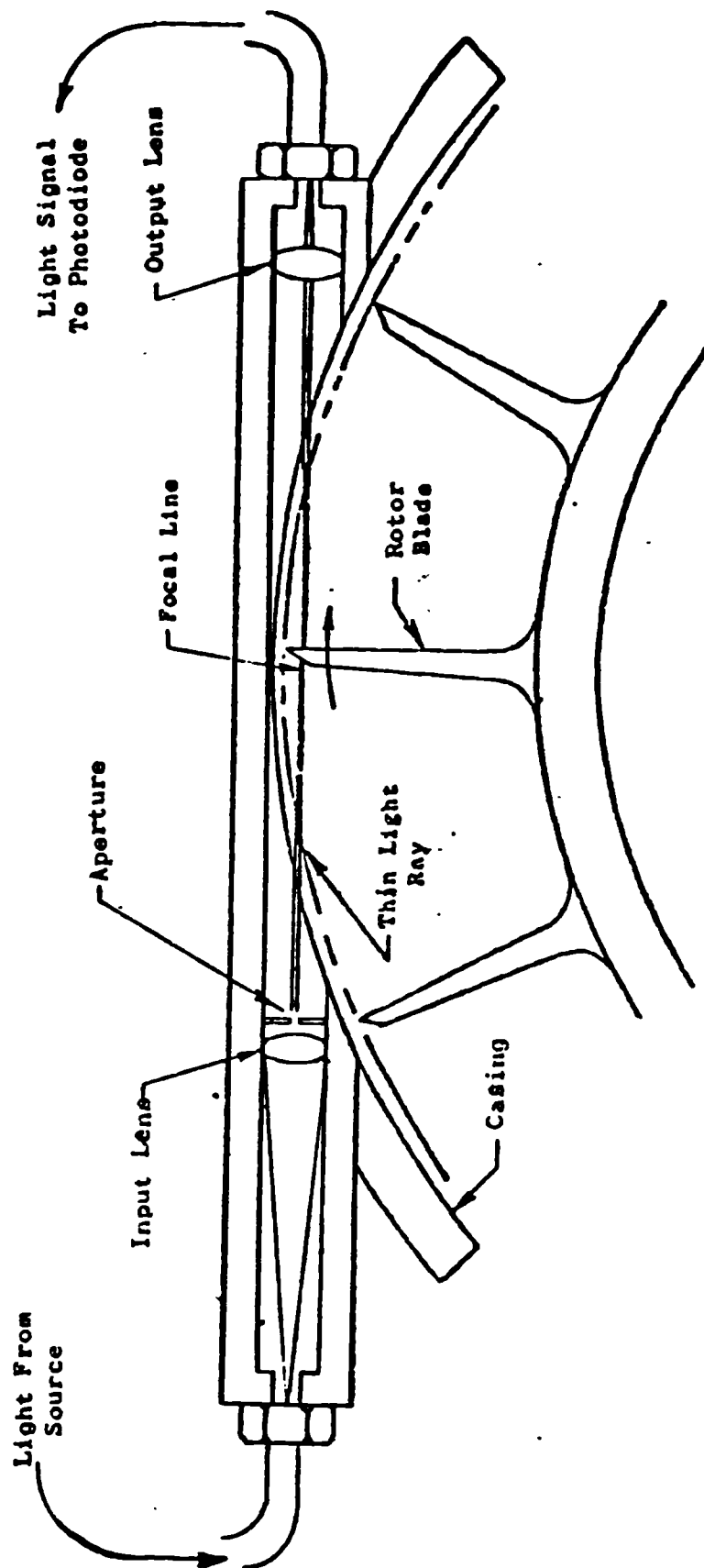


Figure 1.13 Sensing Concept of Optical Tip Clearance Sensor.

slugs, a built-in system calibration is hypothesised. By this means it is argued that the undesirable dependence of the output voltage on rotational speed and target and probe temperatures can be removed from the desired clearance dependence. However, information on the distribution of blade metal temperatures derived during the development of turbine blade internal cooling systems, suggests that severe difficulties will be encountered in attempting to maintain a uniform slug temperature during normal turbine operation. Also the insertion of the high permeability target material in the blade tips represents a non-trivial problem for the blade design and manufacture areas. In addition it is essential that the precise radial location of each target slug is known and maintained over the operating temperature range of the engine in order that the clearance measurements can be corrected for speed and temperature effects. This makes the assumption that the thermal and centrifugal growth of each turbine blade is identical to within 0.05 mm. Experience with measurements made in a turbine development context suggest that this assumption may not be valid.

2.0 MEASUREMENT TECHNIQUE EVALUATION / SELECTION.

Following the survey of previous work in the field of tip clearance measurements, a "brainstorming" approach was adopted within the Measurement Techniques and Analysis Group. This generated a comprehensive list of measurement techniques which were potentially usable in a gas turbine environment. A catalogue of sixteen possible methods was produced and a formal Decision Analysis technique employed in order to produce a short-list which could be evaluated in greater depth.

The short list contained four techniques - two optical based, one microwave and one capacitive based. These four techniques are now considered in more detail.

2.1.0 Optical Triangulation.

This technique does not appear in the short list of potential production clearance measuring systems due to its complexity, its inability to operate at high temperatures without powerful cooling and the close proximity of the optical components to the "dirty" engine gas path. However, despite these disadvantages, it is felt that the system deserves a position in the short list as it is the technique which has had arguably more time and resource devoted to its development than the total resource expended on all the other techniques investigated to date. Although the embodiments of the triangulation principle described in the literature search (Refs.2 to 7 inclusive) are considered unlikely to meet the required system specification, the technique should provide a

useful "control" measurement against which more operationally supportable or production oriented clearance measuring techniques can be evaluated. The confidence in the validity of the data generated by the optical triangulation system is considered to be very high. This high confidence factor stems from the reliance of the technique on simple geometric relationships between the linear position of the light spot on the detector and the clearance of the reflecting target surface from the probe. This relationship i.e. the system calibration, can be demonstrated easily under all conditions of temperature and pressure.

2.2.0 Optical Astigmatic.

This system works on the principle that a light beam which is focussed by an astigmatic lens changes shape as it passes through the focus. A solid object such as a blade tip placed near the focus of such a lens will have a spot of light projected on it, the shape of the spot depending upon the exact position of the target from the lens. A schematic layout of an astigmatic probe is shown in Figure 2.1. In Figure 2.1 View on FF with target at HH, the reflected image of the spot of light which is projected onto the target partially covers four fibre optic bundles each of which transmits the light to a photodiode. The four bundles are arranged at 90 degree intervals around the single fibre optic which transmits the light from the source. In the arrangement shown, each photodiode is illuminated equally. If the target is then moved towards the lens system which is made astigmatic by the use of a cylindrical lens (which has different focal lengths in the

two axis normal to the direction of transmission), the spot of light changes from a circle to a vertical line as shown in Figure 2.1 View on FF with target at GG. Only photodiodes 1 and 3 are now illuminated. If the target is moved away from the lens the spot of light becomes a horizontal line as shown in Figure 2.1 View on FF with target at JJ and only photodiodes 2 and 4 are illuminated. By taking some combination of the photodiode voltages (such as $(V_1 + V_3 - V_2 - V_4) / (V_1 + V_3 + V_2 + V_4)$) the position of the target relative to the lens can be calculated.

This type of clearance probe can be potentially very small and robust. Also the astigmatic lens can be set well back from the blade tips, as compared with the optical triangulation probe, which should minimise the possible problems of lens contamination in a turbine environment.

2.3.0 Microwave Reflectometer.

The proposed clearance system consists basically of a Michelson Interferometer which was first used at microwave frequencies as long ago as 1952. A time of flight system was considered but the small clearances involved in a gas turbine would require a pulse width of less than 16 picoseconds and a timing accuracy of 0.17 picoseconds. A clearance system which utilised the wavelength of a stable oscillator by measuring phase was judged to be a more practical proposition.

A schematic arrangement of the interferometer components is shown in Figure 2.2. Microwave energy from an oscillator enters a hybrid junction at port 1. It is a characteristic of such a junction that power entering at port 1 is equally

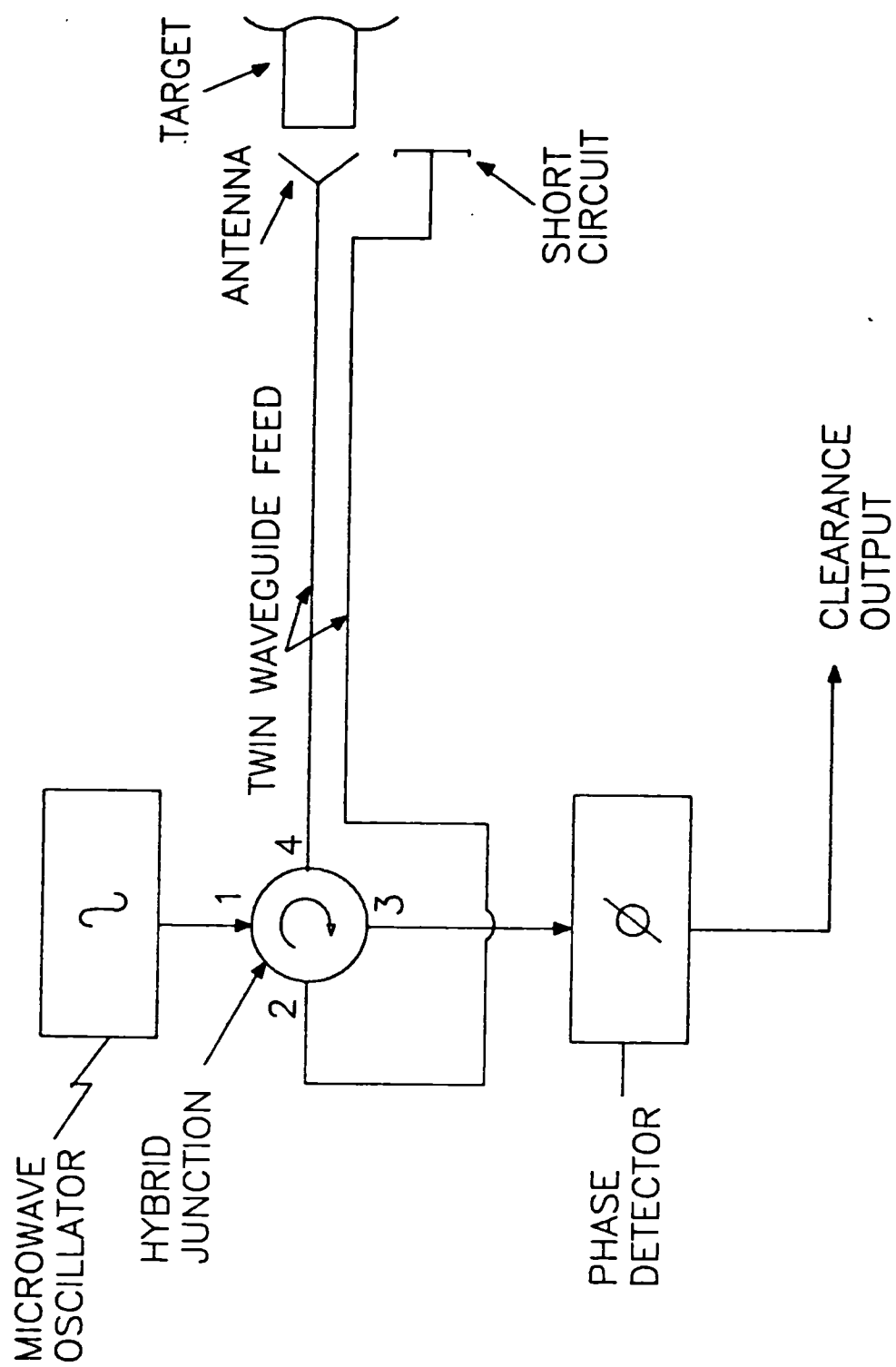


Figure 2.2 Microwave Interferometer Clearance System.

divided between ports 2 and 4. The ports are respectively connected via waveguide to a short circuit (reflectometer reference arm) and an antenna (reflectometer measuring arm) which is illuminating the target, i.e., the turbine blade tips. Signals are reflected from the short circuit and the blade tips and return to the junction via port 2 and 4. The phase difference between these two reflected signals is detected at port 3 and is a measure of the difference in path lengths between the two arms of the reflectometer. To ensure that the effects of temperature changes are minimised, the reference arm of the reflectometer runs adjacent to the measuring arm. In this way temperature variations occurring along the waveguide length are experienced equally by both arms which will expand or contract equally, thus giving a zero differential phase-shift. A resolution of one electrical degree of phase difference between the signals is possible which represents a clearance change of 0.014 millimeters when using a carrier frequency of 30 GHz. (a wavelength of 10mm.). Millimetric microwave devices and systems are currently in routine use on high performance aircraft. Thus the proposed use of such devices in an aircraft engine-mounted clearance measuring system should not require a quantum jump in device technology in order to succeed. The sensing element of the system which is exposed to the high temperatures and pressures could be, in its simplest form, an open-ended waveguide. This sensor is clearly one of the more robust sensors under consideration with a perceived potential for operating at very high temperatures reliably for long periods of time.

2.4.0 Capacitance Technique.

The principle of this clearance measuring technique is based upon the variation of the electrical capacitance formed between an insulated electrode and the target rotor blade tips. Several partially successful systems based upon measurement of this electrical parameter have been described in Chapter 1.4.4, which dealt with previous work in the field of blade tip clearance measurement. It is not proposed at this stage to discuss the way in which the capacitance variations may be transduced into an electrical signal, as this topic is fully explored in the next chapter.

However, whichever transduction technique is used to derive an electrical analogue of the blade tip clearance, the casing mounted probe can be considered simply as a parallel plate capacitor. Neglecting the effects of fringing, the measured capacitance is related to the clearance by the relationship :-

$$C = E_r \cdot E_0 \cdot A / d$$

where :-

C = capacitance in Farads.

E_r = relative permittivity of the dielectric between the electrodes.

E_0 = permittivity of free space in Farads/meter.

A = electrode area in meters squared.

d = electrode separation in meters.

The effective relationship between capacitance and displacement can be determined empirically. However, for the

calibration to remain valid throughout the engine operating envelope, the value of relative permittivity of the dielectric, (air), must remain constant over a wide range of temperatures and pressures. Alternatively the relative permittivity of the dielectric must be known at each engine condition in order that a correction to the measured clearance can be applied. According to Kaye and Labey (Ref.17), the relative permittivity of air minus one is proportional to density assuming the constituents are non-polar permanent gases ie:-

($E_r - 1$) is proportional to Pressure divided by the absolute temperature.

On the basis of this assumption, Figures 2.3 and 2.4 show graphically the variation of relative permittivity of air with temperature and with absolute pressure respectively.

Of considerably greater importance is the way in which the relative permittivity of air varies through a gas turbine when subjected to both temperature and pressure variations. Figure 2.5 defines the performance instrumentation planes for a typical three-spool gas turbine. For a modern civil engine in the 220 kN (50000 lbf.) thrust class, the gas pressure / temperature relationships measured at these planes at sea level and on an ISA day are as follows:-

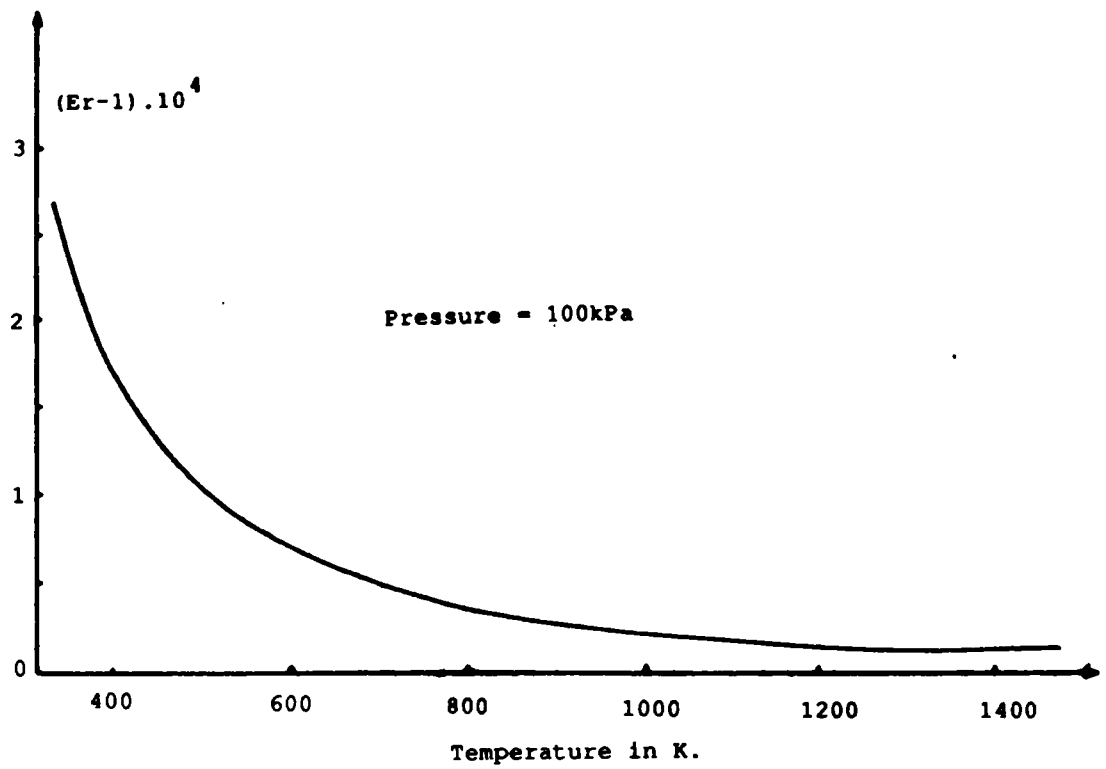


Figure 2.3 Variation of Relative Permittivity of Air with Temperature.

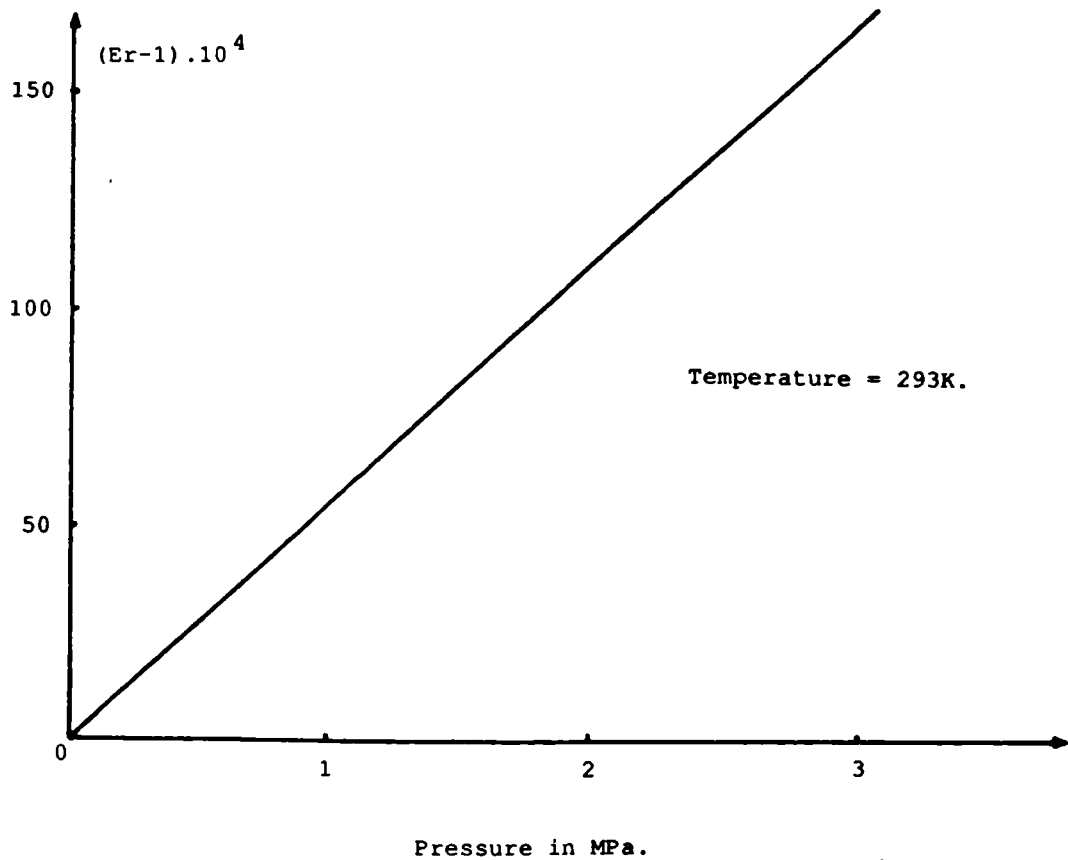


Figure 2.4 Variation of Relative Permittivity of Air with Pressure.

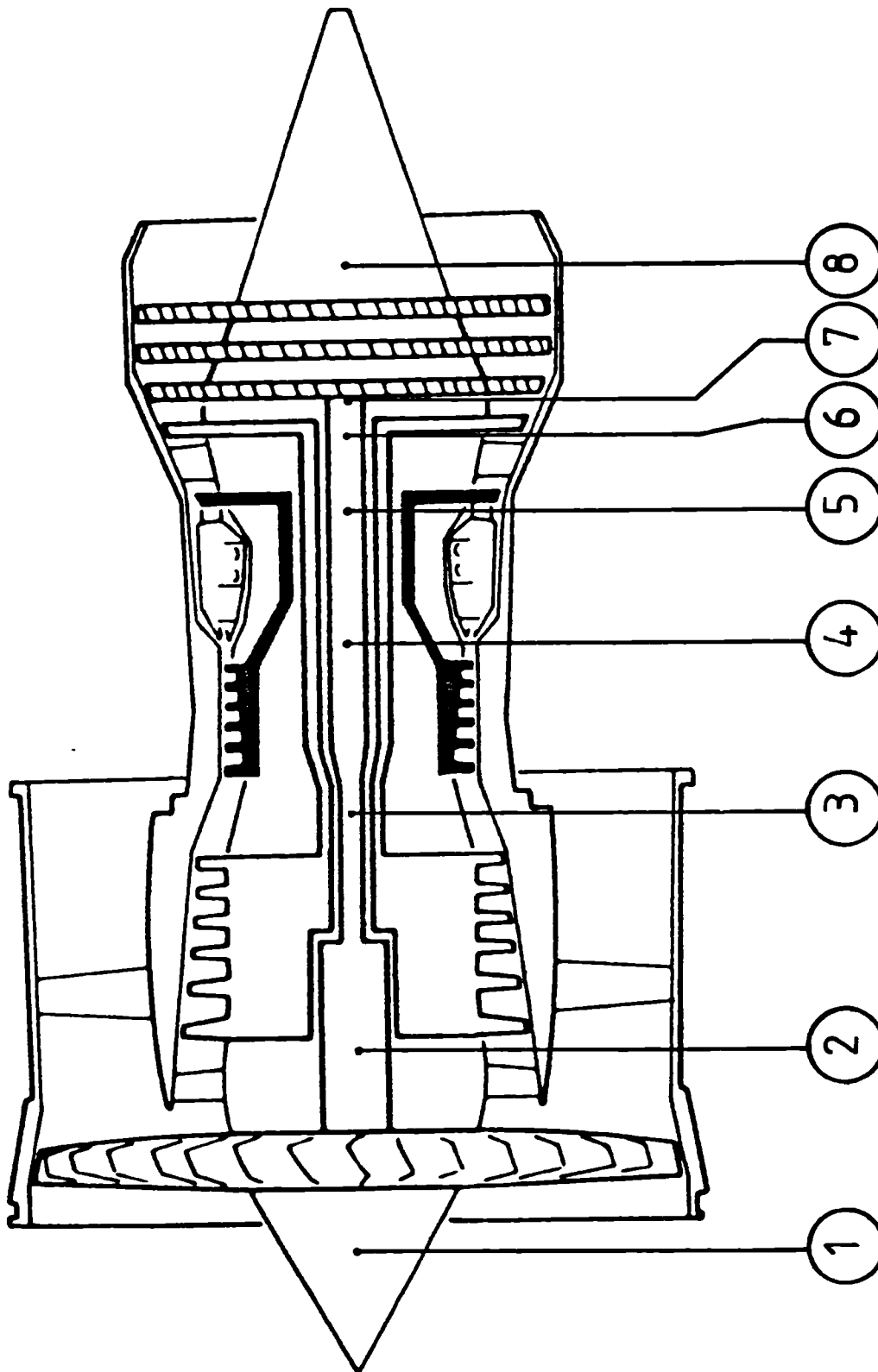
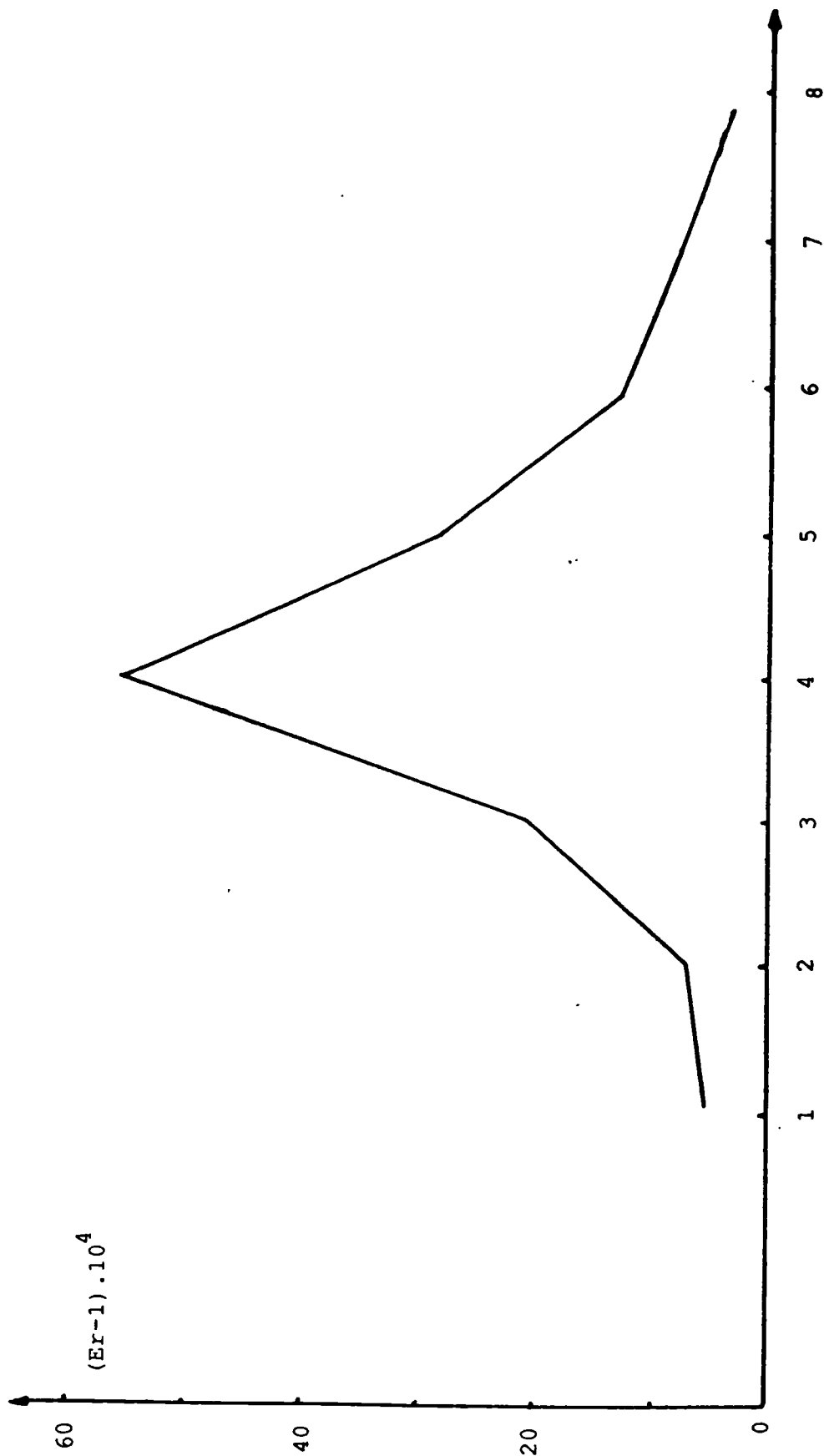


Figure 2.5 Gas Turbine Performance Instrumentation Planes.

Plane	Pressure	Temperature	Location
1	101 kPa	288 K	Fan inlet
2	146 kPa	323 K	Fan delivery
3	693 kPa	526 K	IP compressor delivery
4	2856 kPa	809 K	HP compressor delivery
5	2696 kPa	1500 K	HP turbine entry
6	1003 kPa	1225 K	IP turbine entry
7	489 kPa	1016 K	LP turbine entry
8	169 kPa	797 K	LP turbine exit

Compression of the air from the inlet by the fan, followed by the intermediate and high pressure compressors results in a total pressure multiplication of approximately 28 times. This is accompanied by a rise in temperature of some 500 K. Fuel is then burnt in this compressed air which enters the first high pressure, (HP), turbine at a temperature of 1500 K or more. Gas pressure and temperature then fall as energy is extracted by four more turbine stages before being exhausted at a pressure of 169 kPa and a temperature of 797 K.

This data is used to calculate the relative permittivity of the air at each of the gas turbine measurement planes. The results are plotted graphically in Figure 2.6. The maximum value of permittivity of 1.00564 occurs at Plane 4 (HP compressor delivery) and represents a permittivity deviation of 0.51% from the value at STP (1.000536) and hence a maximum measurement error of 0.51% of reading. The minimum permittivity value of 1.00034 which occurs at Plane 8



Instrumentation Plane.

Figure 2.6 Variation of Relative Permittivity of Air ϵ_r .
Instrumentation Planes.

generates an error of less than 0.02% of reading when using a calibration derived at ambient temperatures and pressures. This performance is well within the specification discussed in Chapter 1.3.2.

The considerations so far have assumed that the working fluid throughout the engine has been air. No allowance has been made for the burning of fuel in the combustor, which affects the gas composition. It has been determined from prior work in the field of combustion research, (Ref.18), that a typical gas turbine exhaust from the hot nozzle contains the following constituents by volume:-

Nitrogen	77 %
Oxygen	17 %
Carbon Dioxide	3 %
Water Vapour	2 %
Traces carbon dioxide, oxides of nitrogen and the inert gases	1 %
	100 %

Using Daltons law of partial pressures, which states that " the pressure exerted by a mixture of gases is equal to the sum of the separate pressures which each gas would exert if it alone occupied the whole volume " ie:-

$$pV = V (p_1 + p_2 + p_3 + \dots p_n)$$

As a first approximation, pV can be considered constant. Thus, the partial pressures are directly proportional to their proportion by volume in the mixture. Hence, as permittivity is directly proportional to pressure :-

$$E_{\text{mixture}} = E_{\text{gas1}}(\% \text{gas1}) + E_{\text{gas2}}(\% \text{gas2}) + \dots$$

Using the values of relative permittivity given in Kaye and Labey (Ref.17) for Oxygen, Nitrogen, Carbon dioxide, Argon and Water vapour, the resultant permittivity for first air, (as a check), and then the combustion products, are calculated.

$$1. \quad E_{\text{air}} = E_{\text{oxygen}}.(0.21) + E_{\text{nitrogen}}.(0.78) + E_{\text{carbon dioxide}}.(0.0003) + E_{\text{argon}}.(0.0097)$$

$$E_{\text{air}} = (1.000494).(0.21) + (1.000547).(0.78) + (1.000921).(0.0003) + (1.000545).(0.0097)$$

$$E_{\text{air}} = 1.000536 \quad (\text{result agrees with published value to 5 decimal places.})$$

$$2. \quad E_{\text{comb.products}} = (1.000494).(0.17) + (1.000547).(0.77) + (1.000921).(0.03) + (1.000545).(0.0097) + (1.00012).(0.0203)$$

$$E_{\text{comb.products}} = 1.000541 \text{ ie } 0.0005\% \text{ error}$$

The level of ionisation present in the combustion products was assessed as this could have a complex effect on the gas permittivity. However it was concluded that at typical combustor temperatures, pressures and gas velocities the ionic

content of the gas above the turbine blades would be negligible.

Hence the conclusion is that the working fluid before and after combustion has taken place, can be considered, practically, to have an invariant value of electrical relative permittivity.

The simplicity of a capacitance based clearance measuring system combined with the high operating temperature capability of the capacitance sensor and the remarkable stability of the permittivity of the working fluid in a gas turbine context, ensures a place in the short list for this technique.

2.5.0 Final Selection.

From the short listed techniques described under Chapter headings 2.1.0 to 2.4.0 inclusive, the following decisions were taken:-

a) To manufacture an Optical Triangulation tip clearance system using published design information and a minimum of innovation. The measurement provided by this system will be used to assess the validity of measurements generated by other measurement systems for the reasons given in para. 2.1.

b) To investigate fully the Capacitance based measurement technique for immediate use in an engine development context and future use in a passenger carrying production

aircraft application.

c) Initiate research at a lower level of activity to investigate the potential of the Optical Astigmatic and Microwave Reflectometer techniques.

This thesis documents the activities concerned with the research, design, development and evaluation of a Capacitance based tip clearance measuring system.

3.0 TRANSDUCTION TECHNIQUES.

In order to assess which capacitance transduction technique represents the optimum choice in a gas turbine tip clearance measuring context, an estimate of the magnitude of the expected capacitance variation is required. Using the formula for the capacitance of a parallel plate capacitor stated in Chapter 2.4.0, the following assumptions were made :-

- * The largest measuring electrode which could be tolerated in current compressor/turbine casing designs is of circular form, 4mm in diameter. A rectangular section electrode was not considered to be a practical proposition because alignment of the electrode with the rotor blade tips could not be guaranteed except at one engine operating condition. This would result in a capacitor where the effective area varied with rotor speed as the blade stagger angle was affected by centrifugal forces and gas loadings..

- * The effective area of the target i.e.the blade tip, is equivalent to another electrode of 4mm diameter.

- * Effects due to fringing are negligible.

At a probe to blade clearance of a) 3.0mm and b) 0.5mm, which represents the minimum and maximum clearances respectively to be measured as defined in Chapter 1.3.0, the capacitance variations resulting from a blade traversing across the probe are :-

$$\begin{aligned}
 \text{a)} \quad C &= E_r \cdot E_0 \cdot A / d \\
 &= \frac{1.00054 \times 8.854 \times 10^{-12} \times \pi((4 \times 10^{-3})^2 / 4)}{3 \times 10^{-3}} \\
 &= 0.037 \text{ picofarads.}
 \end{aligned}$$

$$\text{b)} \quad C = 0.223 \text{ picofarads.}$$

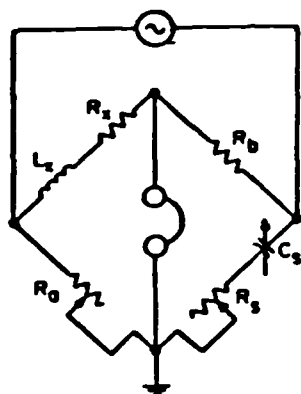
Thus at a probe to blade clearance of 3.0 mm, a capacitance variation in the order of 0.04 pF can be expected due to the passage of a single blade in front of the probe electrode. This value rises to over 0.2 pF capacitance variation at a probe to blade clearance of 0.25mm.

In order to quantify these small changes in capacitance caused by the passing of rotor blades, and hence obtain a measure of each blade to probe clearance, several different transduction techniques have been considered.

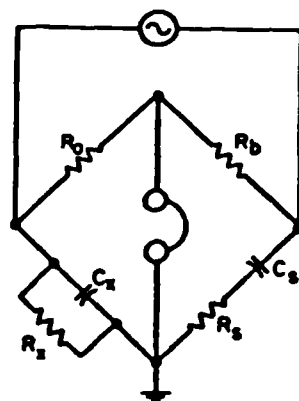
3.1.0 Capacitance Bridge.

The classical method which is generally used to measure small values of capacitance is the a.c. polarised bridge circuit. Hague (Ref.18), Thomas and Clarke (Ref.19), and Helke (Ref.20) describe various bridge configurations, examples of which are shown in Figure 3.1. Arguably the most popular a.c. bridge is the so-called "Blumlein" bridge circuit with tightly coupled inductive ratio arms. Walsh (Ref.21), Starr (Ref.22) and Clarke and Vanderlyn (Ref.23) describe various aspects of the Blumlein bridge but possibly the most lucid explanation of this circuit

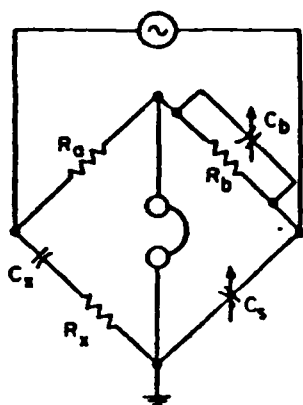
HAY BRIDGE



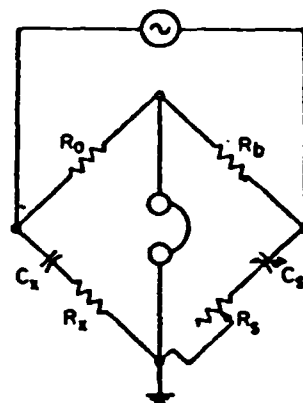
WIEN BRIDGE



SCHERING BRIDGE



SERIES-RESISTANCE-CAPACITANCE BRIDGE



MAXWELL BRIDGE

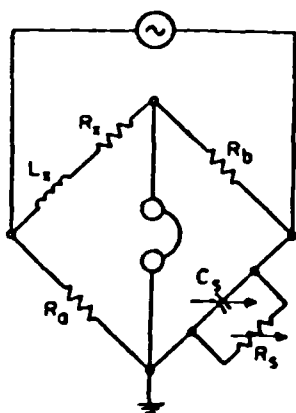


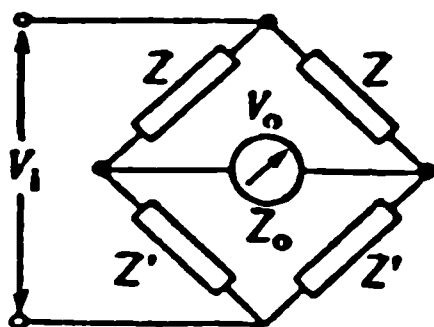
Figure 3.1 Bridge Circuit Configurations.

is given by Neubert (Ref.24).

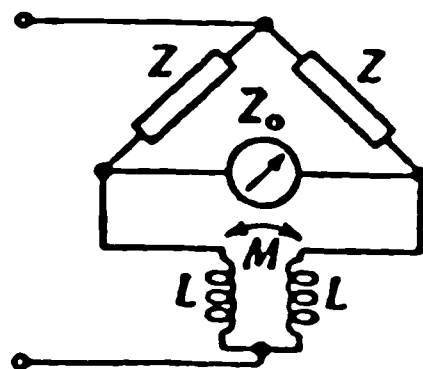
Figure 3.2 a) and b) show the general and capacitative cases of the Blumlein bridges respectively. These bridges are widely used for both inductive and resistive transducers as well as for capacitive transducers, especially at higher carrier frequencies ($>400\text{kHz}$). For 100% coupling between the ratio arm impedances, a voltage drop cannot develop across the ratio arms and it can be shown that any stray or cable capacitance, which would be in parallel with the ratio arms, is ineffective. This important feature of the Blumlein bridge simplifies screening and earthing problems in capacitance bridges of this type. The result is that the zero stability of the circuit is greatly improved.

3.2.0 Constant Voltage.

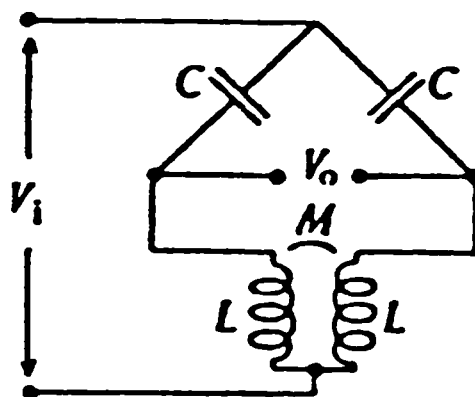
In this transduction technique, the capacitance to be measured is polarised with a d.c. voltage via a high impedance and is the simplest of the three techniques being considered. A schematic diagram of a d.c. polarised constant voltage system is shown in Figure 3.3. It consists of a measuring electrode in the form of a coaxial probe which is capacitively coupled to an amplifier (A). The electrode is polarised from a constant voltage source via a large value resistor (R). The resulting time constant for the network comprising the probe, cable and amplifier input, with an effective shunt capacitance to earth (C) and the resistor (R), is arranged to be typically 100 milliseconds. Thus for changes in capacitance within this network resulting from blades passing the measuring electrode, which take place in less than 10 milliseconds (say), the



a)



b)



c)

Figure 3.2 Blumlein Bridges.

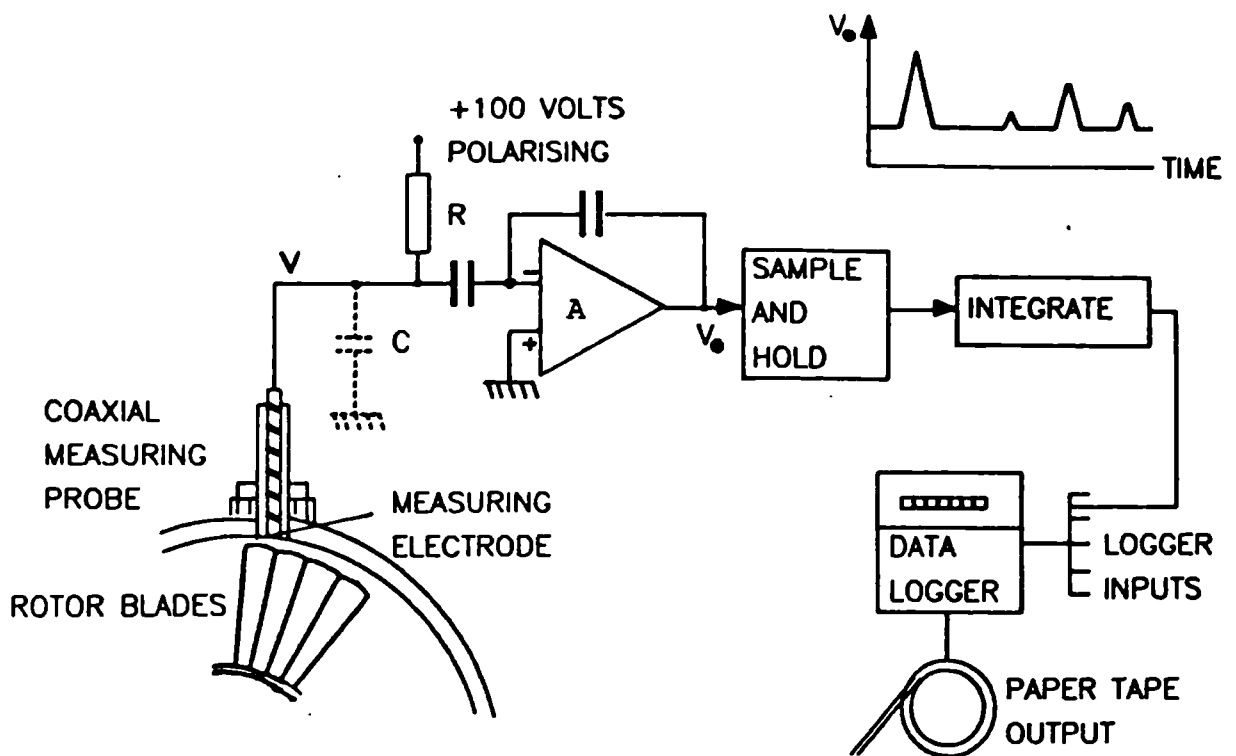


Figure 3.3 Constant Voltage Capacitance Clearance System.

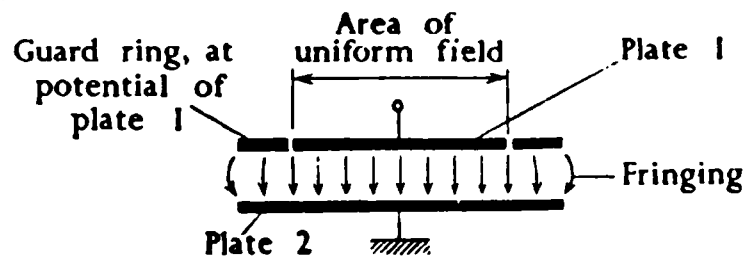


Figure 3.4 Capacitance Probe Guard Electrode.

voltage (V) across the network, ignoring the action of the charge amplifier (A) on the circuit, varies according to the relationship:-

$$Q = C \times V$$

where C = the total effective capacitance of the network; V = the voltage across the capacitance; Q = the electrical charge in the network.

Thus whenever a blade approaches the electrode rapidly, the effective capacitance in the network increases, and the voltage across the network falls. However the charge amplifier (A) detects the voltage change and acts to restore the voltage across the network to the original value. Thus the voltage output from the charge amplifier (Vo), is only a function of the capacitance change within the network, and hence an inverse function of probe to blade clearance, and is independent of the shunt capacitance (C) which can vary significantly with temperature. The voltage (Vo) can either be integrated to give a d.c. voltage which is a function of mean blade clearance or logged separately if the value of each individual blade clearance is required.

3.3.0 Frequency Modulation.

The third technique considered for the measurement of small capacitance changes is one where the variable capacitance is arranged in a resonant LCR circuit. Providing the inductive and resistive elements can be made invariant, the frequency of resonance is an inverse function of the probe to blade tip capacitance, which in turn is an inverse function of probe to blade tip separation. The circuit can be energised by a remote

oscillator via a matched transmission line and coupled into the resonant circuit by means of either a tapping on the inductor or an inductive link. The output frequency of the oscillator is modulated by the blade tip capacitances which, when demodulated, gives a signal similar to that derived from the Constant Charge system described in Chapter 3.2 and can be processed similarly.

3.4.0 Environmental Factors.

In reaching a decision on the transduction technique to be used for the proposed capacitance based turbine tip clearance system, three practical considerations need to be taken into account which are relevant to operation in a gas turbine.

These are :-

1. The capacitance to be measured between a casing mounted probe and the relevant blade tips is unlikely to be loss free. Experience gained with electrically insulated electrodes in the gas path of both rig and engine compressors and engine turbines, indicates that insulation resistance values of greater than 1 Megohm are extremely difficult to achieve and maintain. In the extreme, conditions at the exposed insulator surfaces can vary from cool and damp to very hot and contaminated with conducting combustion products. Insulation resistances as low as 100 kilohms have been observed.

2. The shunt capacitance in any practical probe configuration is some two orders of magnitude greater than

the clearance-related capacitance which is to be measured. The absolute value of this shunt capacitance can be expected to vary considerably in comparison with the small clearance-related capacitance. This is due to changes in temperature of the probe tip and body of many hundreds of K, brought about by the wide operating envelope of the typical gas turbine. Inorganic insulators generally have a high temperature coefficient of permittivity i.e. alumina has a permittivity in the order of 9 and a temperature coefficient of permittivity of +1% per 100K.

3. Experience gained with a simple d.c. polarised capacitance system, similar to that described in Chapter 3.2.0, has identified that in a gas turbine HP Compressor environment, electrical interference of variable severity can be expected. The interference appears to be generated within the compressor, and although the mechanism is not fully understood, compressor rotors are known to become electrically charged by the scrubbing action of the air being compressed. This charge on the rotor then leaks to earth through the compressor bearings, and, in the case of an HP compressor, through the bearings and gears in the external gearbox.

Band-pass filtering in order to remove the noise sometimes improves the situation but has never been totally successful. This has been due to the overlapping of the interfering frequencies with the blade passing frequencies. Attempts to remove the offending signals by correlating the blade clearance measurements with rotor speed proved equally ineffective due to the interfering

signals being frequency locked to harmonics of rotor speed.

In a turbine application, as opposed to a compressor application, combustion of hydrocarbon fuel is taking place just upstream of the tip clearance measuring zone. This results in further degradation of the signal to noise ratio of the clearance measurements, primarily due to the occasional presence of charged particles in the gas stream after combustion.

3.5.0 Guard Circuit Concept.

The effects detailed in the preceding section, imply that the capacitance to be measured, which is the required function of blade tip clearance, can be expected on occasions to have the following properties:-

- a) A low insulation resistance (< 1 Megohm)
- b) Be shunted by a capacitance some two orders of magnitude greater (typically 200 to 400 picofarads)
- c) The absolute value of shunt capacitance can vary by a factor of 2 to 3.

In order to isolate the clearance related capacitance variations from the spurious leakage resistance and shunt capacitance effects, the use of a guard circuit concept is introduced.

Conventionally the use of a guard electrode is a recognised method of eliminating fringing in capacitance transducers.

Figure 3.4 shows a section of a parallel plate capacitor

including a guard ring electrode. The guard electrode is maintained electrically at the same potential as the capacitor measuring electrode, plate 1, thus ensuring a uniform electric field over the active area of the capacitor plates. In this way the variation of capacitance with plate separation is simplified to the theoretical inverse function.

If, however, this guard circuitry is arranged such that it encompasses the capacitance sensing circuitry, with the exception of the measuring electrode, the large shunt capacitance to earth formed by the probe, connecting cable and electronic circuitry will be excluded from the clearance derived capacitance. The capacitance which exists between the measuring circuitry and the guard circuitry has no effect on the measurement of the small clearance related capacitance as both circuits are at all times at the same electrical potential. Thus the effects of temperature induced changes in the shunt capacitance and, using the same logic, changes in insulation resistance, are removed from the clearance measurements.

3.6.0 Capacitance System Proposal.

Three transduction techniques have been considered in the preceeding sections of this chapter, i.e. constant charge, capacitance bridge and frequency modulation. However only one, the frequency modulation system, when combined with a driven screen or guard concept, appears to possess the required combination of characteristics in order to measure accurately the capacitance variations resulting from the passage of rotor blade tips in a gas turbine engine. These are :-

- * The ability to measure very small variations in capacitance in the presence of large values of shunt capacitance.
- * A dynamic response in excess of 100 kHz.
- * The potential of being developed to operate in conjunction with a driven screen arrangement.
- * A low input impedance.

The concept of a frequency modulated capacitance clearance system combined with a driven guard screen is believed to be novel and poses considerable technical challenge.

4.0 SYSTEM DESIGN CONSIDERATIONS.

The discussions contained in Chapter 2.0 concluded that a capacitance based blade tip clearance system appeared to be the one which would satisfy the measurement specification in a gas turbine environment. Chapter 3.0 examined the various techniques which could be employed in order to transduce the clearance related capacitance variations into an electrical signal suitable for recording or control purposes. The frequency modulated oscillator technique was concluded to offer the required characteristics but only if it could be developed to incorporate a driven guard screen concept. Such a system could be expected to comprise the following elements :-

- a) A measuring probe which would be test vehicle mounted and would contain the capacitance sensor, the oscillator, (or modulator), the frequency of which would be modulated by the capacitance variations and the circuitry necessary to drive the sensor guard screen.
- b) A ground station remote from the test vehicle containing a demodulator, which would convert the frequency variations of the oscillator into a varying analogue voltage. Also circuitry for providing automatic frequency control of the oscillator.
- c) An integrator to generate an electrical signal which would be a function of the mean blade tip clearance of the compressor or turbine stage being measured in the

test vehicle.

d) A data collection and recording system capable of producing time history plots of tip clearance variations.

A schematic diagram of such a system is shown in Figure 4.1. The factors affecting the design of each of the system elements are now considered in turn, together with an examination of the system calibration requirements.

4.1.0 Measuring Probe - Sensor.

The sensor electrode forms one plate of a variable capacitor, the value of which is the required function of blade tip clearance. The second plate of the capacitor is formed by the rotor blade tips which are of necessity electrically earthed to the test vehicle casings via the bearings, seals and occasionally gear trains. It is clear that the sensor electrode must be located in the compressor or turbine casing immediately above the rotor blades whose clearances are to be measured. The electrode must also be electrically insulated from the casing in which it is mounted and must remain so under all temperatures and pressures generated by the test vehicle, assuming that slave cooling facilities (water or air from external sources), are not utilised. Casing temperatures of typically 800K and 1100K can be expected respectively in the high pressure compressor and turbine of a modern aero gas turbine.

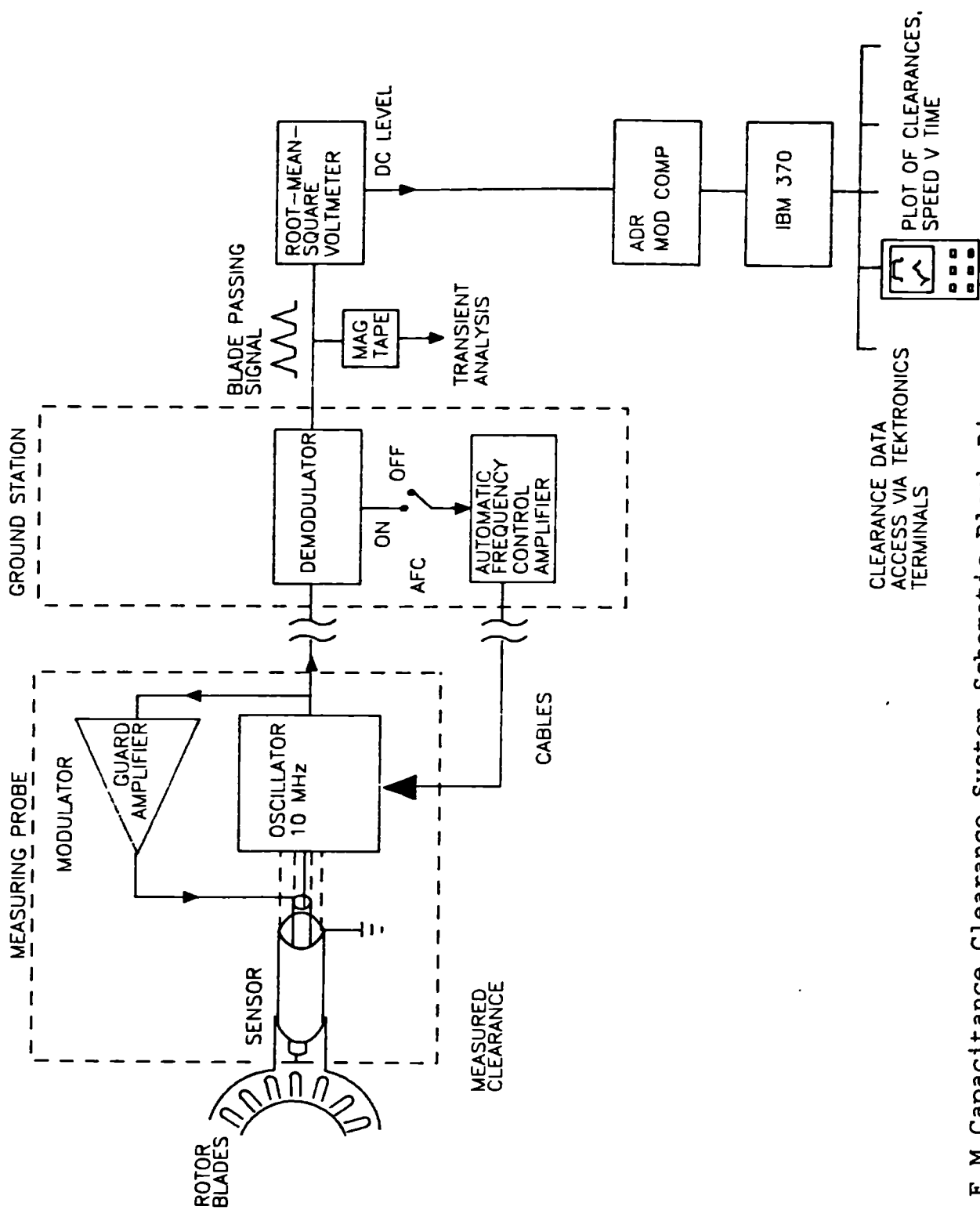


Figure 4.1 F.M.Capacitance Clearance System Schematic Block Diagram.

The maximum outer diameter of the sensor which could be accommodated in the casing of a high pressure turbo machine, without either significantly weakening the casing or introducing unacceptable over blade tip aerodynamic losses, is approximately 5mm. This constraint in turn gives rise to the maximum practical diameter for the sensor measuring electrode of 4mm. Figure 4.2 shows two schematic diagrams of capacitance sensors.

The proposed construction utilises an alumina bead insulator which is brazed into a metallic housing. An electrode is in turn brazed into the alumina insulator thus producing an all brazed probe assembly with an electrode insulated from earth. An alumina insulated double-screened cable is shown brazed into the probe tip assembly to connect the sensing electrode to the oscillator. The outer screen of the cable is at earth potential, but the inner screen is connected to the amplifier driving the guard circuitry. The inner screen is terminated physically as close as practical to the sensing electrode, thus keeping to a minimum the value of non-varying shunt capacitance to earth.

A truly coaxial probe construction was investigated in which the guard electrode was terminated flush with the surface of the sensing electrode. However this design only resulted in a reduction in unguarded or shunt capacitance 0.5 pF when compared with the mechanically simpler design shown in Figure 4.2. In addition, the effective shunt capacitance within the modulator and the double screened cable connecting the sensor to the modulator was found to be 19 pF and 1.8 pF respectively. The 1.8 pF shunt capacitance resulted from the 1% inefficiency in the guard circuit amplifier when driving a

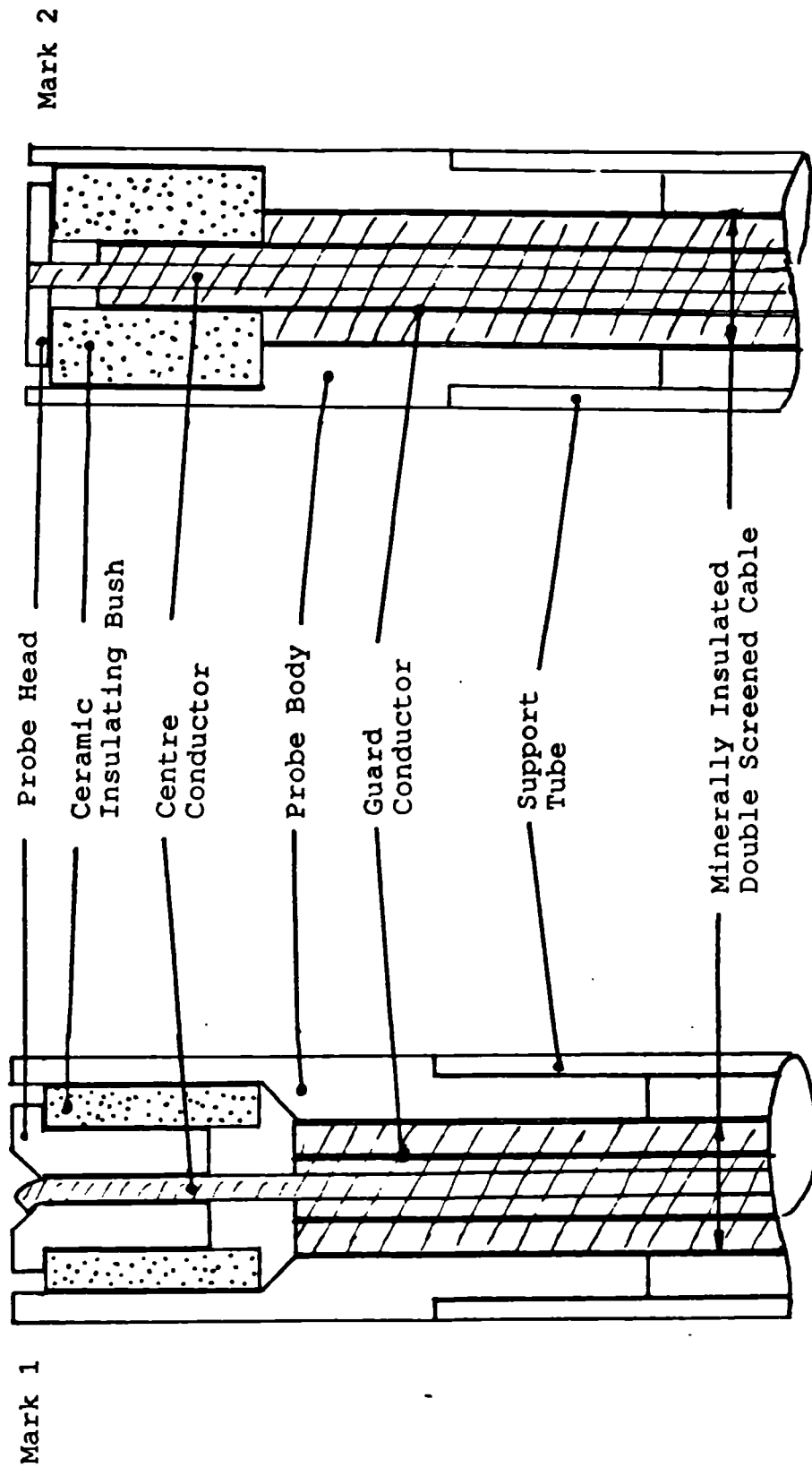


Figure 4.2 Measuring Probe - Sensor.

reactive load represented by a capacitor of 180 pF. It was concluded that the mechanical complexity and potential unreliability of a sensor design which reduced the shunt capacitance of the system by 0.5 pF in 20.8 pF, and hence marginally increased the system sensitivity, was not justified.

Several different assembly designs were initially considered, which would have avoided the potential difficulties of fabricating a ceramic and metal brazed assembly, which were capable of operation at high temperatures and were resistant to thermal shock. However, all the alternative non-brazed designs resulted in probe assemblies which were considerably larger than a comparable brazed design. In addition only the brazed design was considered capable of producing a guaranteed hermetic seal of the probe interior from the external environment. Previous experience of operating electrically insulated probes in a gas turbine environment has shown that for repeatable, good quality results over a long period, the inside of a probe must remain dry. This means that all the joints in the probe must be gas-tight. The combination of water/kerosene mixtures inside a cold engine during the start cycle followed by extreme temperature transients can lead to probes suffering a permanent loss of insulation resistance due to the ingress of contaminants which subsequently cannot escape. The metal to metal brazed joints in any probe construction generally should not cause any problems, but ceramic to metal brazed joints can be expected to cause difficulty.

4.1.1 Reactive Silver Braze.

The initial batch of probes was assembled using an alumina insulator in the form of a circular bead (Degussit Al23-99.7% pure) and housings and electrodes of Kovar (proprietry name of Nylo-K). Kovar is an alloy of nickel, cobalt and iron (Ni 29% ; Co 17% ; Fe 54%) and was selected for this application primarily because its coefficient of linear expansion with temperature is closely matched to that of the alumina insulator to which it must be brazed (approximately 8×10^{-6} /degree C). The reactive braze material used was a silver/copper wire, 0.5mm diameter with a 10% titanium core.

The results superficially appeared to be excellent after the assembly had been heated to a temperature of 1000K in a vacuum. The braze had wetted both the Nilo-K and the alumina and had flowed freely leaving no voids or apparent braze defects. However, when the brazed joints were sectioned for examination, it became clear that the braze did not flow into the capillary gaps which had been designed between the metal and ceramic components. Also the adhesion of the braze to the alumina surface was poor.

The success of this reactive braze method relies on a good vacuum to prevent the reactive component of the braze, the titanium, from combining with any surrounding oxygen gas in preference to the intended reaction with the oxygen in the alumina and the consequent bonding with the alumina via the intermediate compound Ti_2O_3 . It was concluded that with the vacuum facilities available at that time, a vacuum of 10^{-4} Torr was inadequate, 10^{-5} Torr being subsequently

recommended.

4.1.2 Silver Braze to Metallised Ceramic.

The conclusion reached in 4.1.1 regarding the inadequacy of the available vacuum brazing facilities for reactive brazing led to the investigation of an alternative approach using alumina bushes which had been pre-metallised using a painted-on Molybdenum/Nickel mixture fired onto the alumina at high temperature. A conventional high temperature vacuum braze material (silver;copper;palladium) could then be used to braze the probe components.

This method appeared to solve all the previously experienced problems. The braze wetted the Nilo-K components and the metallised alumina well and flowed fully into the capillary gaps. The brazed joints looked good visually and were successfully pressure tested. However the first time the probe tips were heated to a temperature in excess of 650K in the laboratory, the insulation resistance between the electrode and the housing fell from typically >100 Gigohms to <1 Kilohm over a period of 15 minutes to 1 hour. The problem was discovered to be due to the contamination of the alumina insulator surface in the annular gap between the electrode and the housing with a conducting deposit. A microprobe scan of this surface quickly indicated that the contamination consisted mainly of molybdenum and silver. The contamination could easily be removed by a light abrasive cleaning of the annular insulator area, but returned once the probe was heated above the 650K. Various test pieces were

fabricated in an attempt to minimise the contamination by covering the feathered edge contact of braze to metallising to alumina. This edge becomes exposed to the air when the braze and metallising are removed in the annular recess, separating electrically the electrode from the earthed housing. In short this approach was unsuccessful.

4.1.3 Gold Braze to Metallised Ceramic.

In an attempt to avoid the silver contamination of the alumina surface after exposure to high temperatures, a gold/nickel eutectic braze (Orobraz 950) was evaluated using a similar process to that described in section 4.1.2. Again the braze flowed well and wetted the metallised alumina and Nilo-K surfaces. Unexpectedly, after exposure to temperatures in excess of 900K for many hours no signs of the previously experienced contamination appeared.

To summarise the ceramic to metal bonding investigation:-

a) Braze - reactive Ag;Cu;Ti: Alumina - no metallising:
Result - weak joint, no surface contamination.

b) Braze - non-reactive Ag;Cu;Pd: Alumina - Mo/Ni
metallising: Result - excellent mechanical joint,
electrically unusable due to conductive surface
contamination of insulator.

c) Braze - non-reactive Au/Ni: Alumina - Mo/Ni
metallising: Result - excellent mechanically, no

contamination of insulator.

When a braze/metallised ceramic assembly involving silver and molybdenum is heated to temperatures in excess of 650K at ambient pressures, volatile compounds of both silver and molybdenum appear to sublime onto the adjacent alumina surface. This contamination has a high electrical conductivity and quickly shorts the centre electrode to the earthed sleeve. By using a gold/nickel braze with a molybdenum nickel metallising combination, thus eliminating copper and silver, the contamination problem is avoided, probably due to the vapour pressures of gold and nickel being higher than silver. The molybdenum metallising layer may be better masked by the more refractory gold/nickel braze or may even be dissolved/dispersed in the braze, thus immobilising the molybdenum.

4.2.0 Measuring Probe - Modulator.

The measuring probe modulator is considered to be the most critical part of the blade tip clearance measuring system. For this reason the behaviour of the oscillator circuit, which forms the heart of the modulator, is examined in some detail. The prime purpose of the modulator is to transduce the capacitance variations detected by the sensing electrode as the rotor blades pass underneath, into a signal whose instantaneous frequency is a function of the instantaneous value of capacitance. As discussed in the earlier chapters, circuitry for powering the guard screen must form an integral part of the modulator circuitry if the potential advantages of using a frequency modulated transduction technique are to be realised. Additional circuitry for driving the oscillator signal along potentially long transmission lines must also be incorporated in the modulator along with some form of voltage stabilisation to power the oscillator. It is expected that the entire modulator will reside on the test vehicle and thus may be subjected to appreciable temperature transients. The thermal performance of the modulator is thus of paramount importance and it is proposed to include some form of automatic frequency control in the measurement system from the outset.

4.2.1 The Oscillator.

The function of the oscillator circuit is to react to the

capacitance variations caused by the rotor blades passing the sensing electrode. This reaction will take the form of a change in frequency of the oscillator.

Various recognised oscillator designs were considered for their suitability for this application, such as the Colpitts, Hartley and Clapp (Refs.25,26,27,28). Schematic diagrams for these three popular designs are shown in Figure 4.3.

An oscillator circuit consists of basically two parts; an active device with power gain, such as a transistor and a feedback network that determines the operating frequency. Of the two the feedback network is the more critical as it determines the frequency of oscillation, the thermal stability, the sideband levels, harmonics and the output noise level. Figure 4.4 shows schematically the feedback networks associated with the three most popular oscillator circuits. In order that any of the circuits should oscillate, the networks must feedback enough power to the input of the transistor to sustain the oscillations. The product of the feedback network losses and the gain of the active device must be exactly equal to one for conditions of equilibrium to be achieved. In practice this product is arranged to be somewhat greater than one in order that oscillations can start and build up to a useful level. The amplitude of oscillation is eventually limited to a constant value by various non-linearities within the transistor. Additionally the feedback network must produce a phase shift in the signal being fed back such that it is exactly in phase with the signal already at the input to the transistor. The total phase shift of the feedback network and transistor must be exactly zero or 360 degrees.

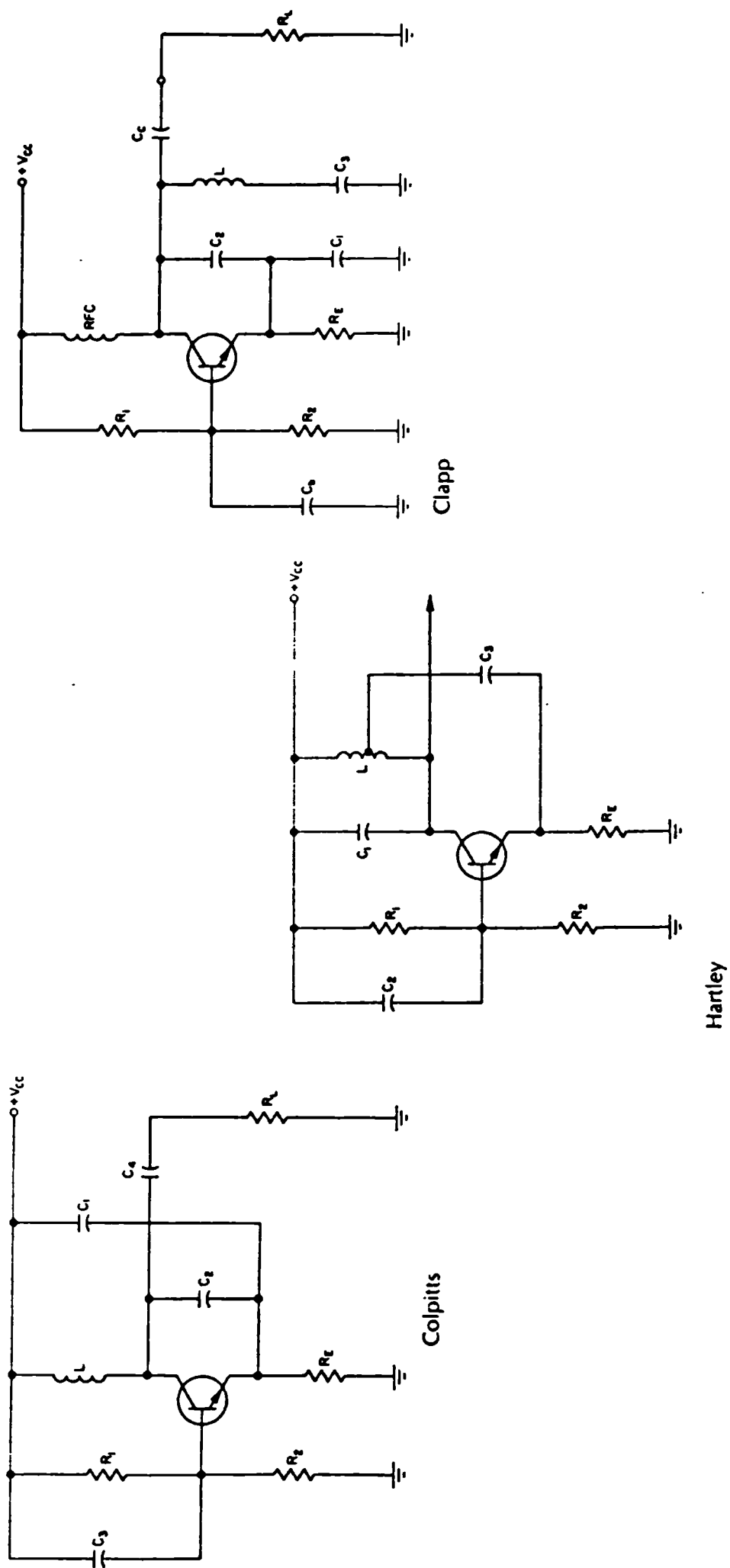


Figure 4.3 Schematic Diagrams of Three R.F.Oscillators.

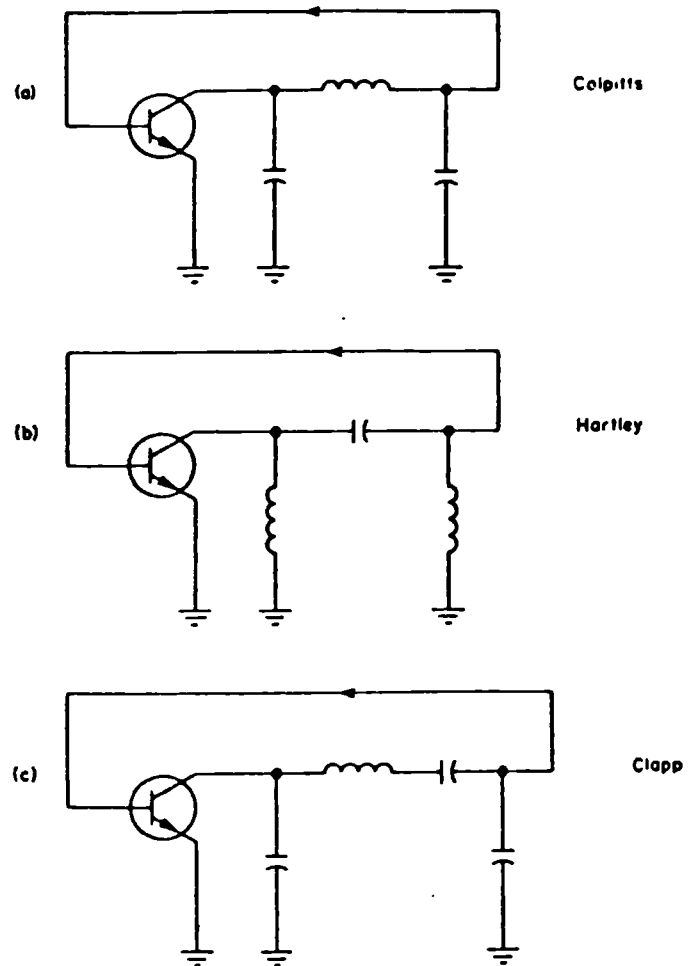


Figure 4.4 Oscillator Feedback Networks.

The Hartley design was chosen for further investigation and development for the prime reason that the feedback network has only one capacitor which determines the frequency of oscillation. Hence, in an application where only one capacitor is varied by a small amount, this circuit can be shown to have a greater frequency sensitivity than any of the alternatives.

4.2.2 Oscillator Circuit Analysis.

The full Hartley oscillator circuit is shown in Figure 4.5. Resistors R_1 and R_2 are biasing resistors and are bypassed by a large value capacitor, C_2 so are not part of the active circuit. The tuned circuit is comprised of capacitor C_1 and inductor L and the feedback network consists of a tapped proportion of the inductor L and the capacitor C_3 . The oscillator load is represented by the resistor R_L , which is connected to the collector by a large value capacitor, C_4 , which is strictly for dc isolation.

The equivalent circuit of the Hartley oscillator, ignoring the components associated with biasing the transistor, is shown in Figure 4.6 a) for a transistor common-base configuration. This circuit can be re-drawn and simplified by referring the emitter parameters back to the primary side of the coil, Figure 4.6 b) and c).

Assuming solutions for the natural response of the circuit are in the form :-

$$v_c = Ae^{pt}$$

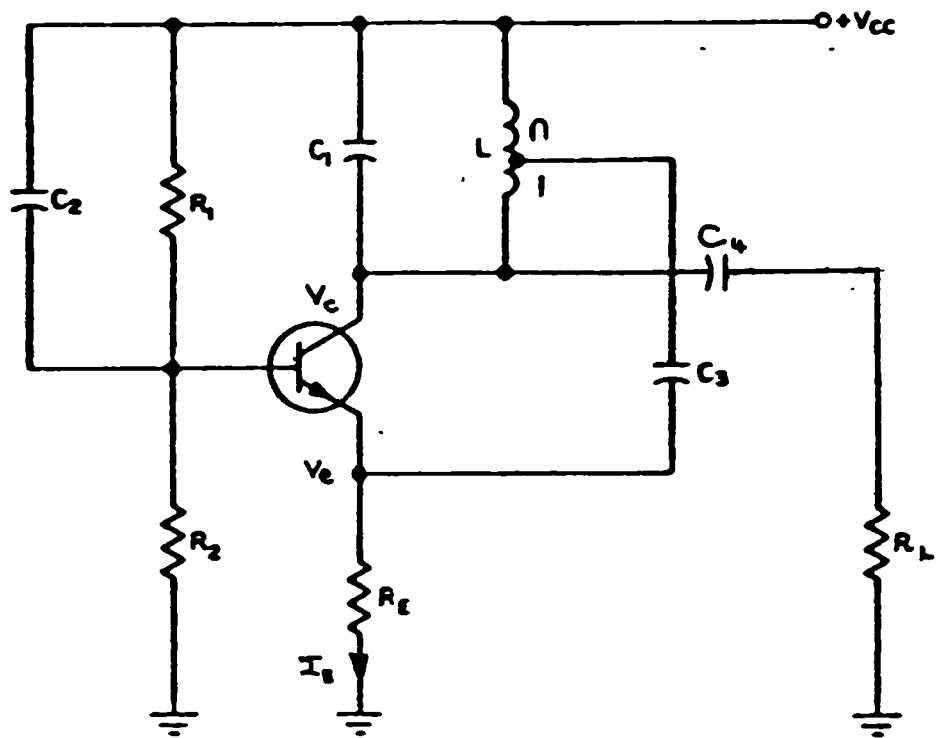
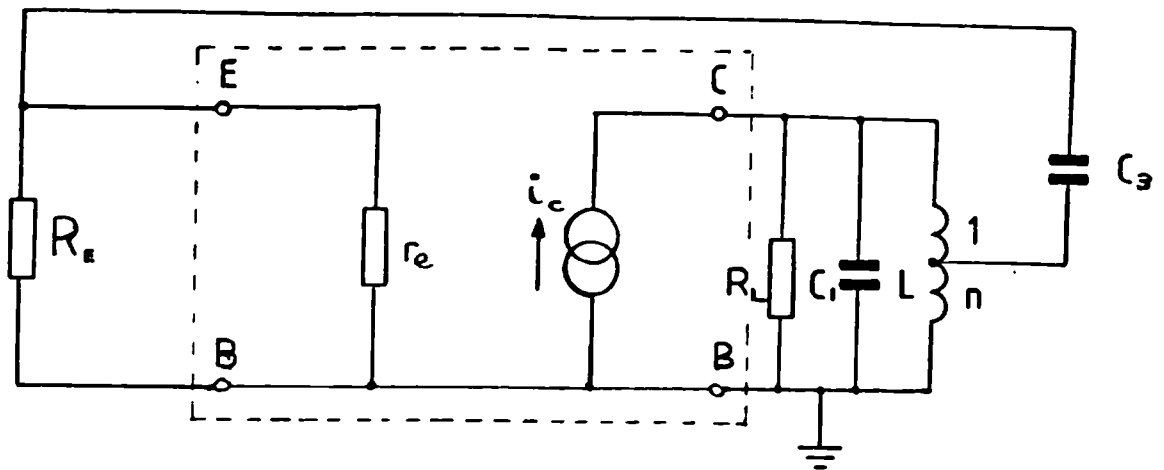
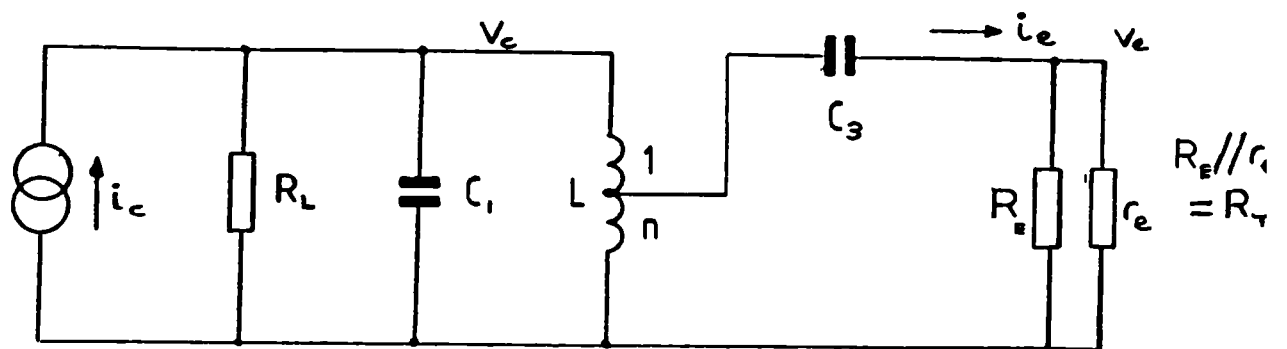


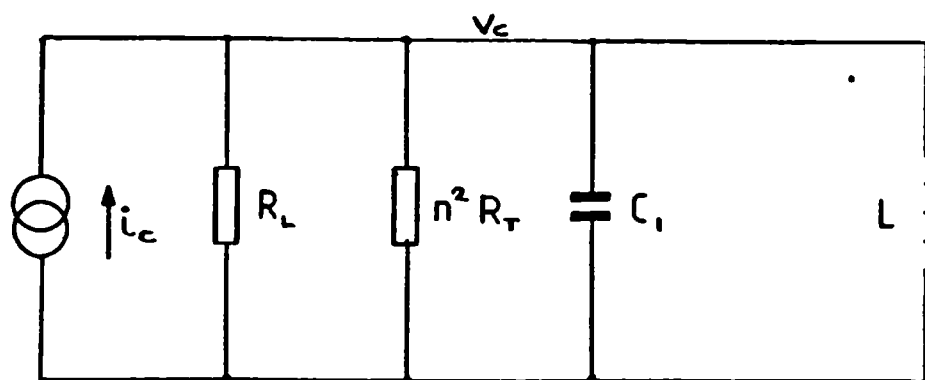
Figure 4.5 Hartley Oscillator Circuit.



a) Transistor with Feedback (Common-base Configuration)



b) Simplified Equivalent Circuit



c) Reconfigured Equivalent Circuit

Figure 4.6 Hartley Oscillator Equivalent Circuits.

Thus:-

$$dv_c/dt = pAe^{pt} = pv_c$$

$$d^2v_c^2/dt^2 = p^2Ae^{pt} = p^2v_c$$

Then:-

$$i_c = v_c/R_L + v_c/n^2R_T + v_cpC_1 + v_c/pL \dots\dots\dots 1)$$

The secondary has $v_e = v_c/n$ induced in it.

So:-

$$i_e = v_c/nR_T \dots\dots\dots 2)$$

But:- $i_e \approx i_c$

So putting 1) = 2) :-

$$v_c/nR_T = v_c(1/R_L + 1/n^2R_T + pC_1 + 1/pL)$$

Giving :-

$$p^2C_1LnR_L + pL(n^2R_T + R_L - nR_L) + nR_L = 0$$

From which :-

$$p = \frac{-(L(n^2R_T + R_L - nR_L)) \pm \sqrt{(L(n^2R_T + R_L - nR_L))^2 - 4C_1LnR_L^2}}{2C_1LnR_L}$$

= - $\alpha \pm jw$ (if the expression under $\sqrt{}$ is negative)

For instability (oscillation) $-\alpha$ is positive.

ie:-

$$nR_L > n^2 R_T + R_L$$

$$(n - 1)R_L > n^2 R_T$$

$$R_L > n^2 / (n - 1) \cdot R_T$$

For minimum R_L to meet this criterion (ie for strongest oscillation):-

$$n^2 / (n - 1) \cdot R_T \text{ is minimum}$$

Thus:-

$$d(n^2 / (n - 1)) R_T / dn = 0 \quad (R_T = \text{constant})$$

$$2nR_T / (n - 1) - n^2 R_T / (n - 1)^2 = 0$$

$$2n = n^2 / n - 1$$

$$n = 2 \dots\dots\dots 3)$$

Thus the optimum turns ratio for maximum instability is 2:1. This is achieved for a tapped coil, (which behaves as an auto-transformer), when the tap is at the mid position on the coil.

At the oscillation frequency of the circuit, which approximates to :-

$$\omega = 1 / \sqrt{LC_1} \dots\dots\dots 4)$$

the collector load reduces to R_L in parallel with $n^2 R_T$
 $(= R_L')$

Hence :-

$$v_{ce}/i_c = R_L'$$

When power is first applied to the oscillator both v_{ce} and i_c grow exponentially until the negative excursions of either the voltage or the current reach zero, when limiting occurs. If the collector voltage falls to zero before the collector current, voltage limiting occurs. This is undesirable from a waveform and frequency stability criteria because whenever v_{ce} is zero the transistor effectively shorts out the tuned circuit.

The oscillator circuit is thus designed so that I_C is small and hence i_c limits before v_{ce} . During this non-linear operating region of the circuit when current limiting occurs, the transistor appears as an open circuit across the tuned circuit and hence has minimal influence on the waveform and stability.

The Hartley oscillator design investigated is very similar to that shown in Figure 4.5. However in order to improve the temperature stability of the base bias network, use is made of the diode compensation technique (Ref.29). Temperature changes in a silicon transistor affect the $V_{be}:I_b$ relationship (the base-emitter voltage/base current relationship) and may cause a change in the quiescent transistor base current, I_{bq} . By including a similar forward biased base/emitter junction in the transistor base bias network the variation of I_{bq} is

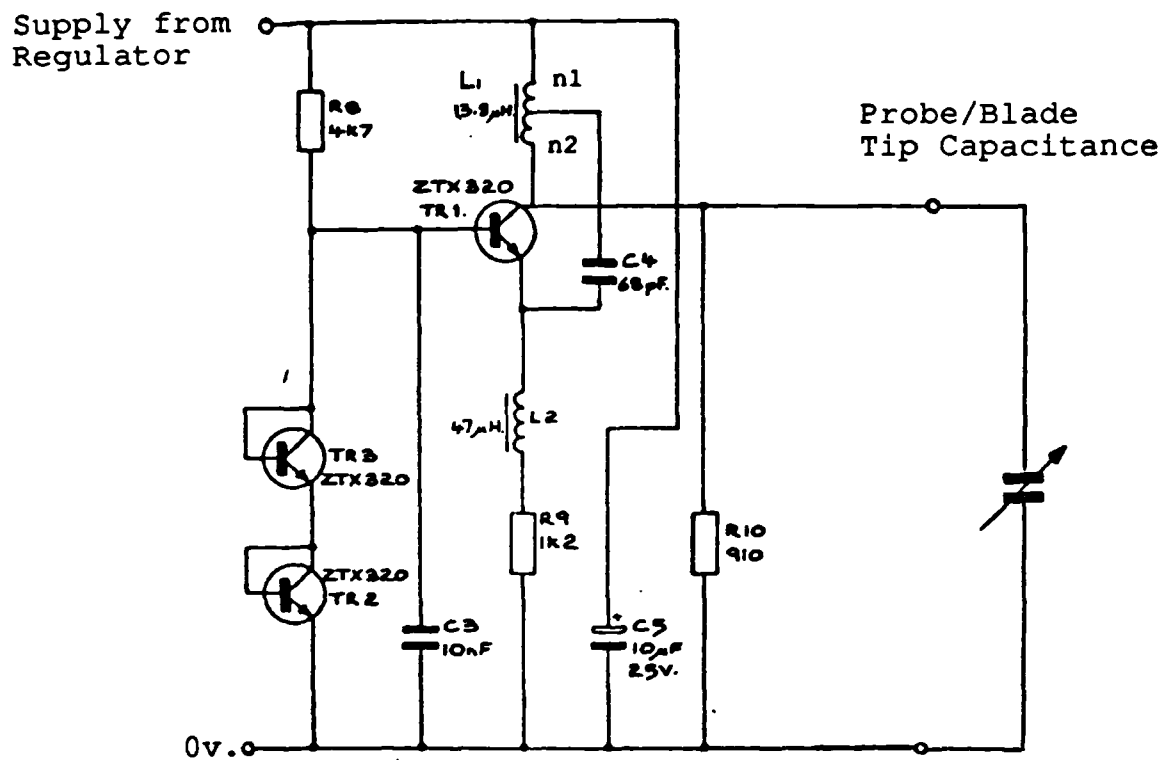
drastically reduced. By insertion of two diodes in series in the bias network, temperature induced increases in beta (the current amplification factor), can be compensated for. The tuned circuit is resonated at an approximate frequency of 10 MHz.using component values calculated from the relationship expressed in equation 4).

By use of an RF vector meter the effective capacitance C1 (Reference Figure 4.3) was measured in a prototype circuit to be 19 picofarads. A toroid wound with 60 turns of 34 SWG enamelled copper wire produced an inductor of 13.8 microhenries. When the inductor was inserted into the oscillator circuit an operating frequency of 9.88 Mhz.was generated (calculated oscillation frequency was 9.83 MHz.) The close agreement between the calculated and measured frequencies implies that there are no other significant reactances in the circuit.

A frequency of 10 MHz.was chosen as being optimum from consideration of the following combination of factors: sensitivity to capacitance changes, stability, circuit design layout criteria and the ready availability of devices and circuitry to demodulate the frequency modulated carrier containing the clearance data.

The circuit design with component values is shown in Figure 4.7. The tapping position on the coil alters the feedback around the transistor and it was determined theoretically that for the strongest oscillations, the tap must be at the coil mid point (equation 3).

The oscillator was designed to be heavily loaded by the 910 ohm resistor, in order that any loss of insulation resistance between the measuring probe electrode and earth caused by



L2 = 3k0 at 10 MHz to reduce load on tuned circuit

Figure 4.7 F.M. Hartley Oscillator Design.

contamination of the alumina surface, would have a negligible effect on the operation of the oscillator. Insulation resistances as low as 100 kilohms had been measured during the use, in a turbine, of sensors similar to the capacitance measuring probe. For this reason the mid-coil tap position was chosen to give the most robust oscillations.

The coil tap position was explored experimentally whilst measuring the oscillator transistor collector swing and validated the theoretical prediction that V_C was a maximum when the coil was tapped at its mid-point.

During the exploration of the coil tap position, it was observed that the tapping which generated maximum oscillator output also produced a maximum oscillator frequency deviation for a fixed capacitance change. This effect is shown in Figure 4.8 where the clearances between a measuring electrode and a rotating target are plotted against the output from a f.m. demodulator.

The explanation for the coincidence of maximum oscillator output with the maximum frequency sensitivity of the circuit to capacitance changes lies in the fact that when the oscillator output is at a maximum, the transistor mean collector voltage also reaches a maximum value. The maximum mean collector voltage results in a minimum mean collector capacitance, which is effectively shunting the tuning capacitance of the resonant circuit. Thus it follows that when the output from the oscillator is at a maximum the circuit is most sensitive to external capacitance, (or inductance), variations.

Several experimental circuits involving varactor diodes in the

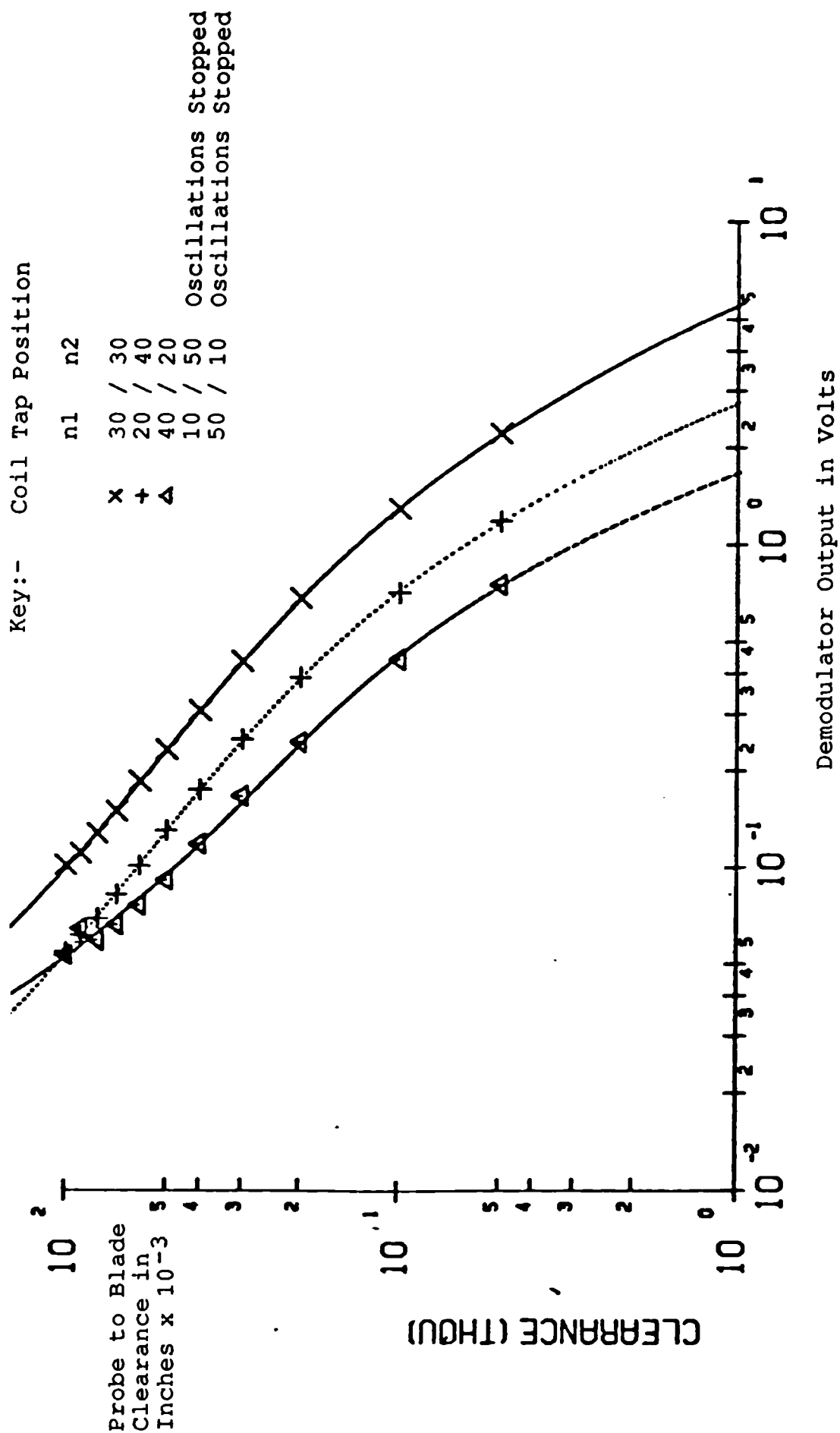


Figure 4.8 Plot of Effect of Coil Tap Position,

resonant circuit were investigated in order to obtain a means of automatically controlling the oscillator centre frequency by means of an error voltage. Although the majority were effective in maintaining frequency control during temperature excursions of the oscillator, all tended to reduce drastically the sensitivity of the circuit to clearance related capacitance changes due to the added shunt capacitance. During the investigation of the oscillator circuit parameters, the frequency was plotted against supply voltage and the results are shown plotted in Figure 4.9. It was decided at this point, after the abortive testing with varactor diodes, to make full use of this voltage/frequency relationship without incurring the desensitising effect of capacitively shunting the resonant circuit.

The oscillator voltage/frequency dependency results from the variation of thickness of the collector/base depletion layer in the oscillator transistor with voltage which varies the collector/base capacitance. In the case of the transistor chosen for the oscillator, a general purpose, high temperature, VHF/UHF, NPN, silicon device (ZTX 320 or BFW 97), the collector/base capacitance is in the order of 6 to 8 picofarads at a V_{ce} of 4 volts. The higher the supply voltage, the wider the depletion layer and the lower the inter-electrode capacitance which results in a small increase in frequency if the transistor is part of an oscillator circuit. The plot of oscillator frequency versus oscillator supply voltage (Figure 4.9) shows typically a 1 MHz. decrease in frequency for a reduction in supply voltage of 7 volts. This magnitude of frequency change can be expressed in terms of a capacitance change in the resonant circuit of the order

Oscillator Frequency in MHz.

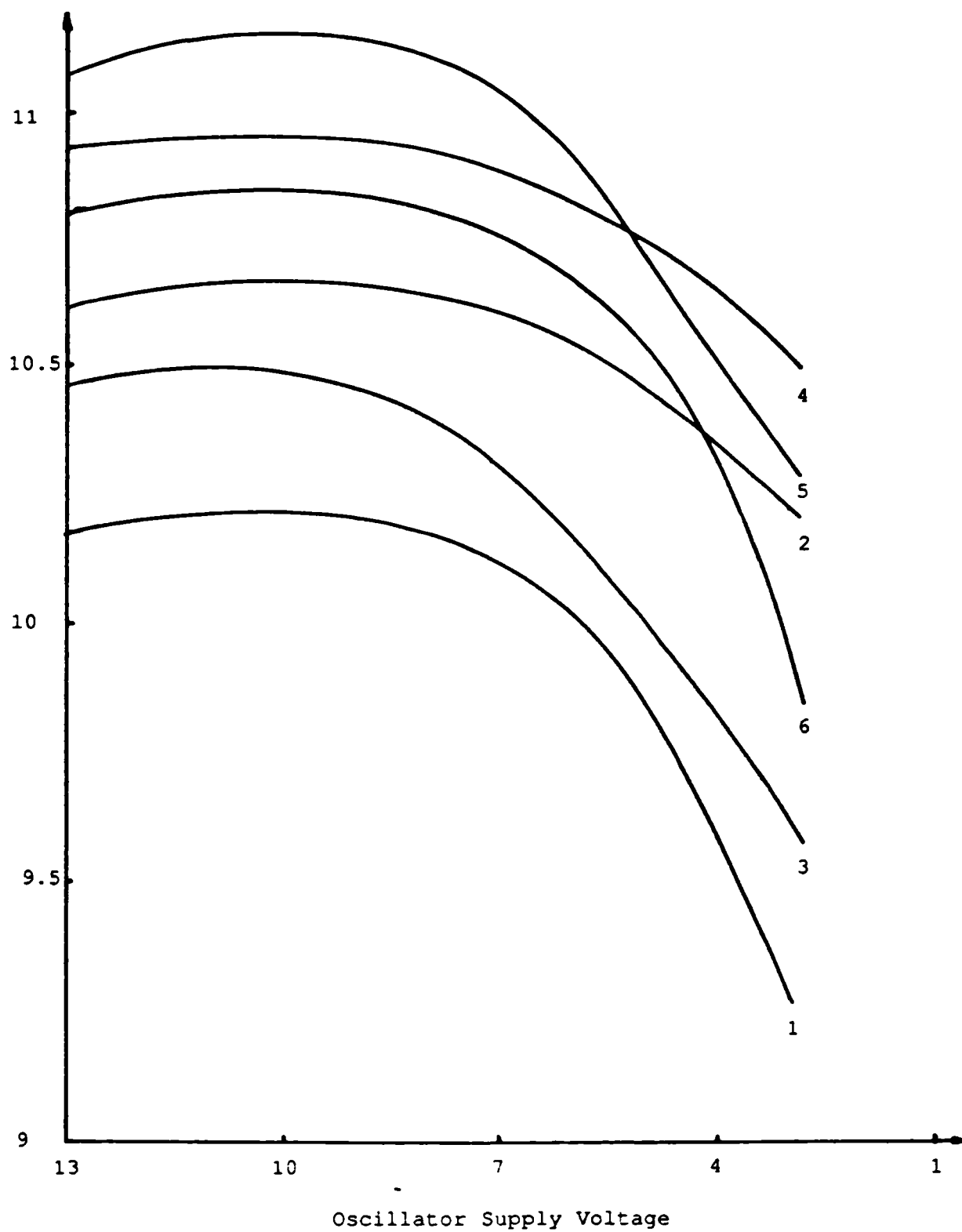


Figure 4.9 Oscillator Frequency v Supply Voltage.

of 4 picofarads. As this observed effective capacitance change agrees well with the expected change in collector/base capacitance for the ZTX 320 transistor used in the oscillator circuit, the explanation of the behaviour of the circuit to supply voltage variations was considered valid.

The temperature performance of a typical oscillator is shown plotted in Figure 4.10. From a batch of six oscillators evaluated, each, bar one, displayed a negative coefficient of frequency with increasing temperature of 0.01% per degree Centigrade. This change in frequency with oscillator temperature was almost exactly the value which had been predicted when considering the temperature stability of the toroidal inductance alone. For the T50-6 iron powder toroid a positive temperature coefficient of inductance of +0.011% per degree Centigrade was specified.

The non-typical oscillator possessed a positive frequency temperature coefficient. The reason for this non-typical behaviour was eventually traced to an incorrectly identified iron toroid on which the coil was wound. Replacing the spurious toroid corrected the deviant behaviour.

4.2.3 The Oscillator Regulator.

In the context of the modulator, the regulator is required to operate from an AFC voltage derived from the demodulator circuit (typically ± 2 volts) and vary the supply voltage to the oscillator circuit (3 to 13 volts). A high temperature T0100 packaged MIL specification regulator was chosen (SN52723L) and connected as recommended in the manufacturers

Oscillator Frequency in MHz.

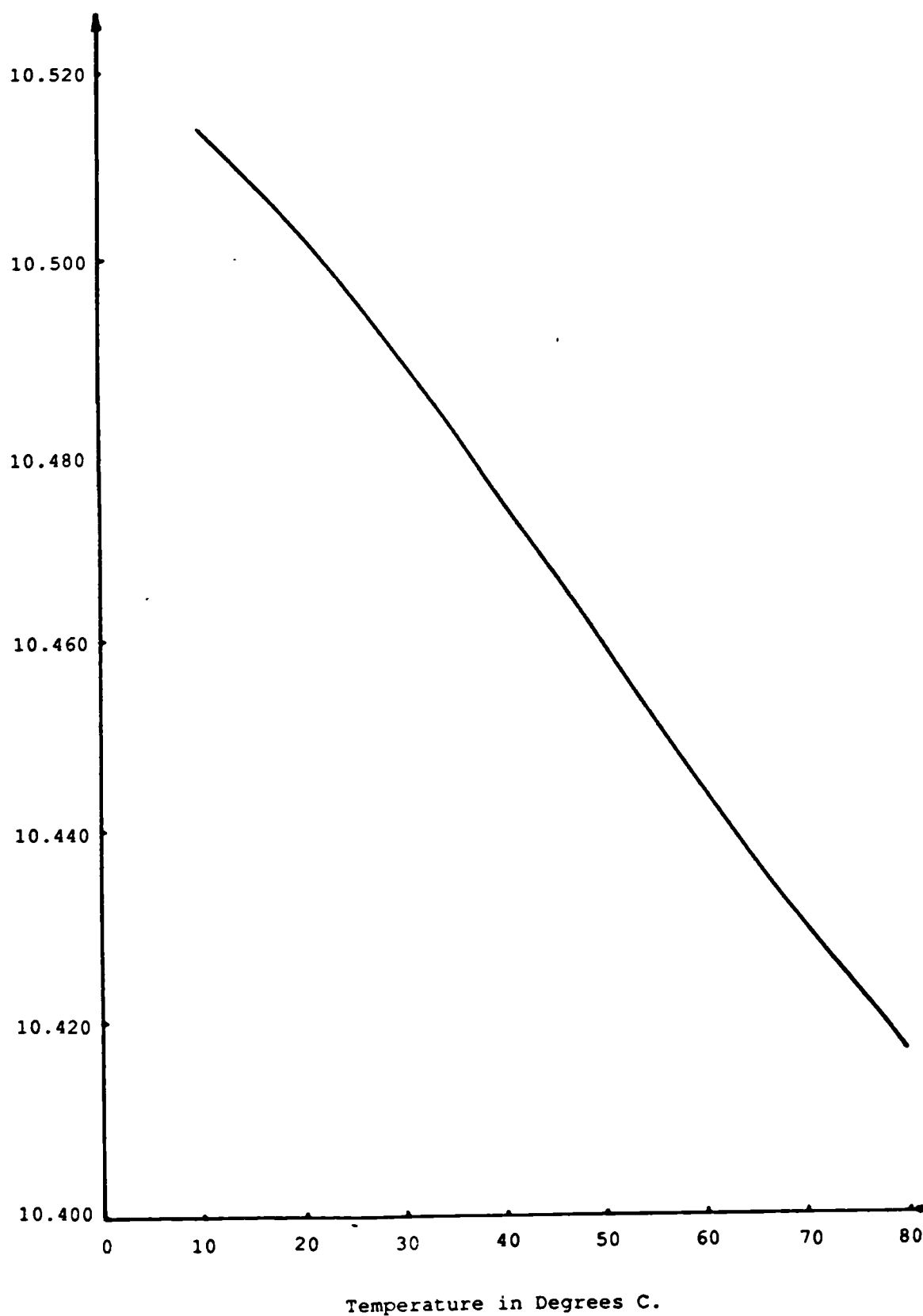


Figure 4.10 Oscillator Frequency v Temperature.

application notes. Care was taken to ensure that the inputs to the regulator were adequately decoupled at 10 MHz. to ensure stability of operation. The developed circuit with component values is shown in Figure 4.11.

4.2.4 The Guard Circuit Amplifier.

Functionally, the guard amplifier must ensure that the instantaneous voltage between the sensing and guard electrodes is zero. Thus the need is simply for a unity gain amplifier, capable of powering a reactive load represented by the total capacitance of the guard screen to earth. The double screened alumina insulated cable used in the construction of the sensor assembly typically has a capacitance 720 pF/meter between inner and outer screens and 350 pF/meter between inner screen and the centre conductor. Only the inner screen to earthed outer screen capacitance effectively loads the guard amplifier. Temperature tests were performed on the alumina double screened and also on a lower temperature (maximum 200 degrees C.) PTFE insulated double screened cable. This cable possessed a lower capacitance per meter than the high temperature cable, due to the increased overall diameter and the lower value of permittivity of PTFE relative to alumina. These results are shown graphically in Figures 4.12 and 4.13. The alumina insulated cable displayed a capacitance versus temperature characteristic which increased in value rapidly with temperature. At 600 degrees C. the capacitance had increased by 40% from the value at room temperature. The capacitance /temperature characteristic for the PTFE insulated

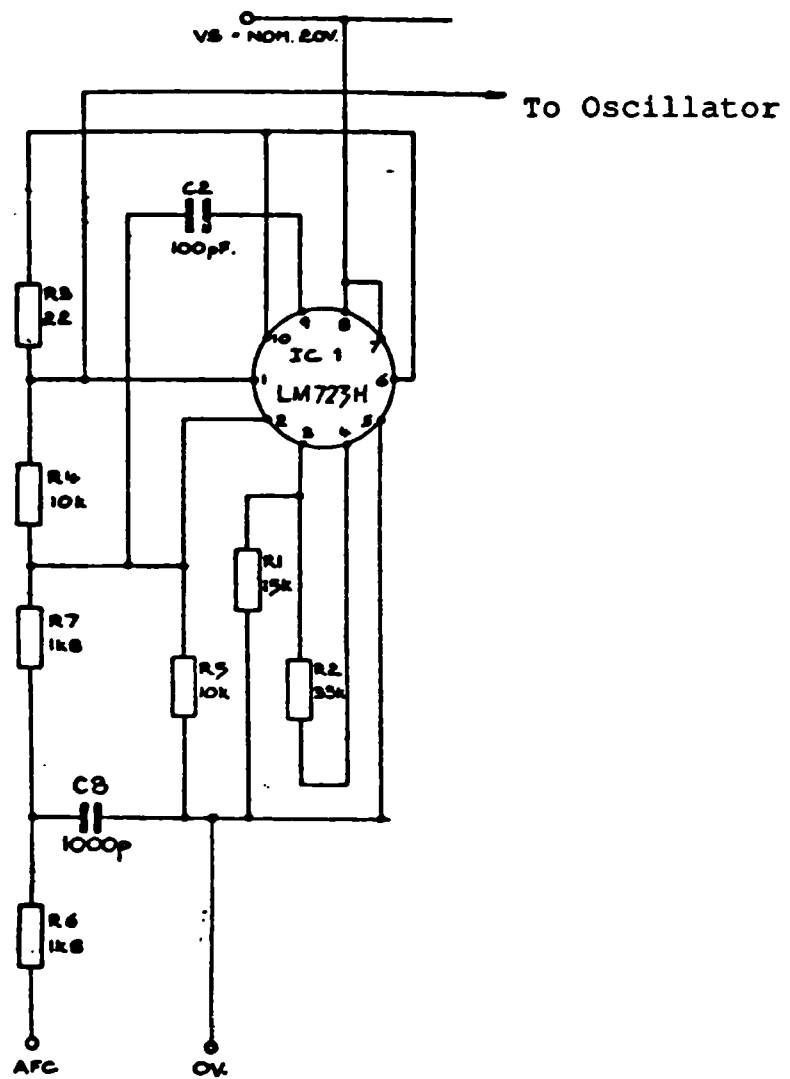
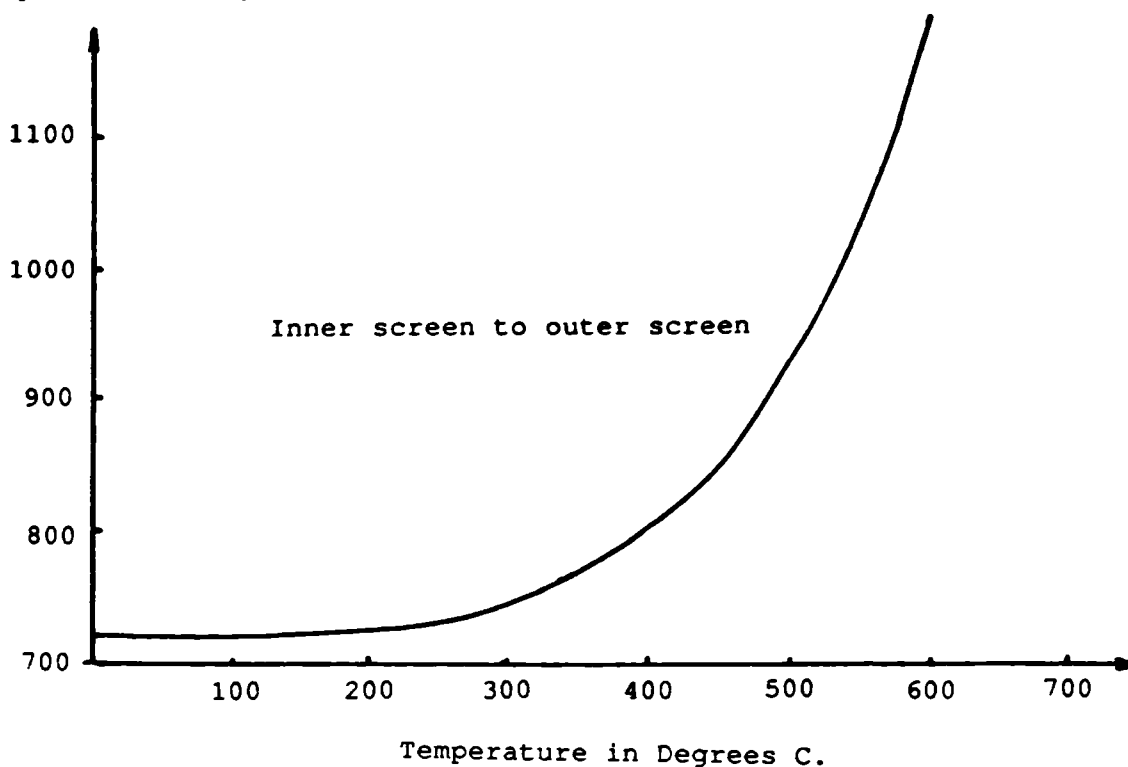


Figure 4.11 Oscillator Voltage Regulator.

Capacitance in pF / meter



Capacitance in pF / meter

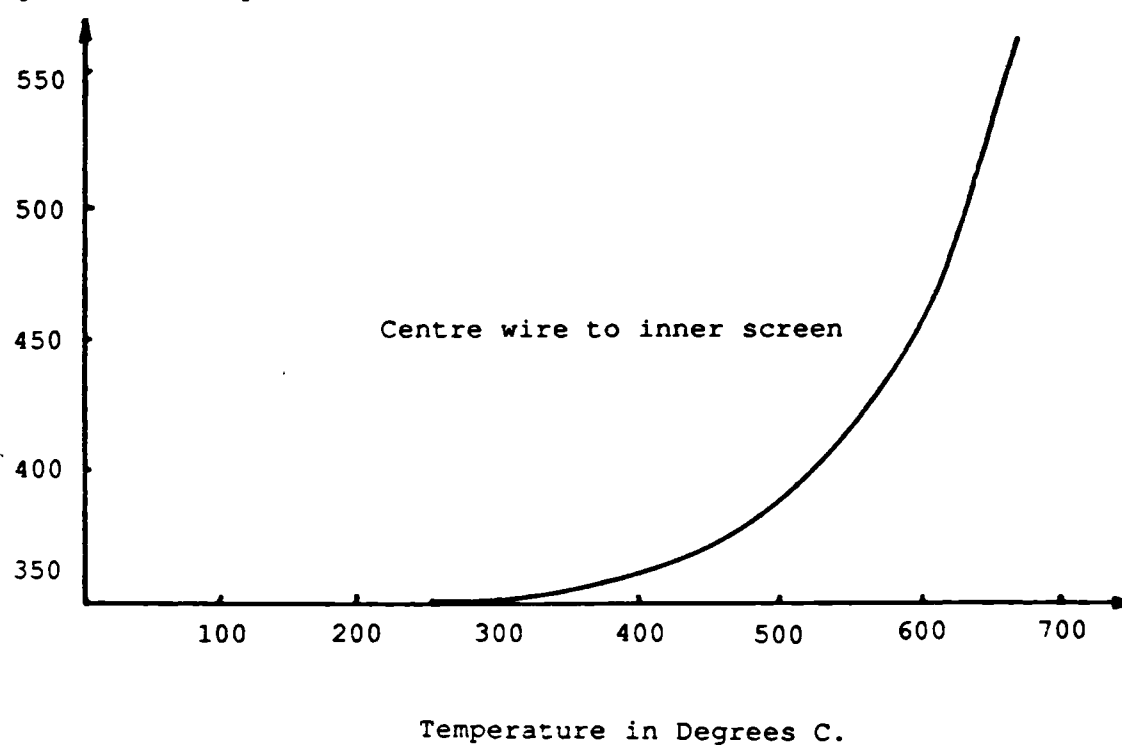


Figure 4.12 Capacitance of Alumina Insulated Double-Screened Cable v Temperature.

Capacitance in pF / meter

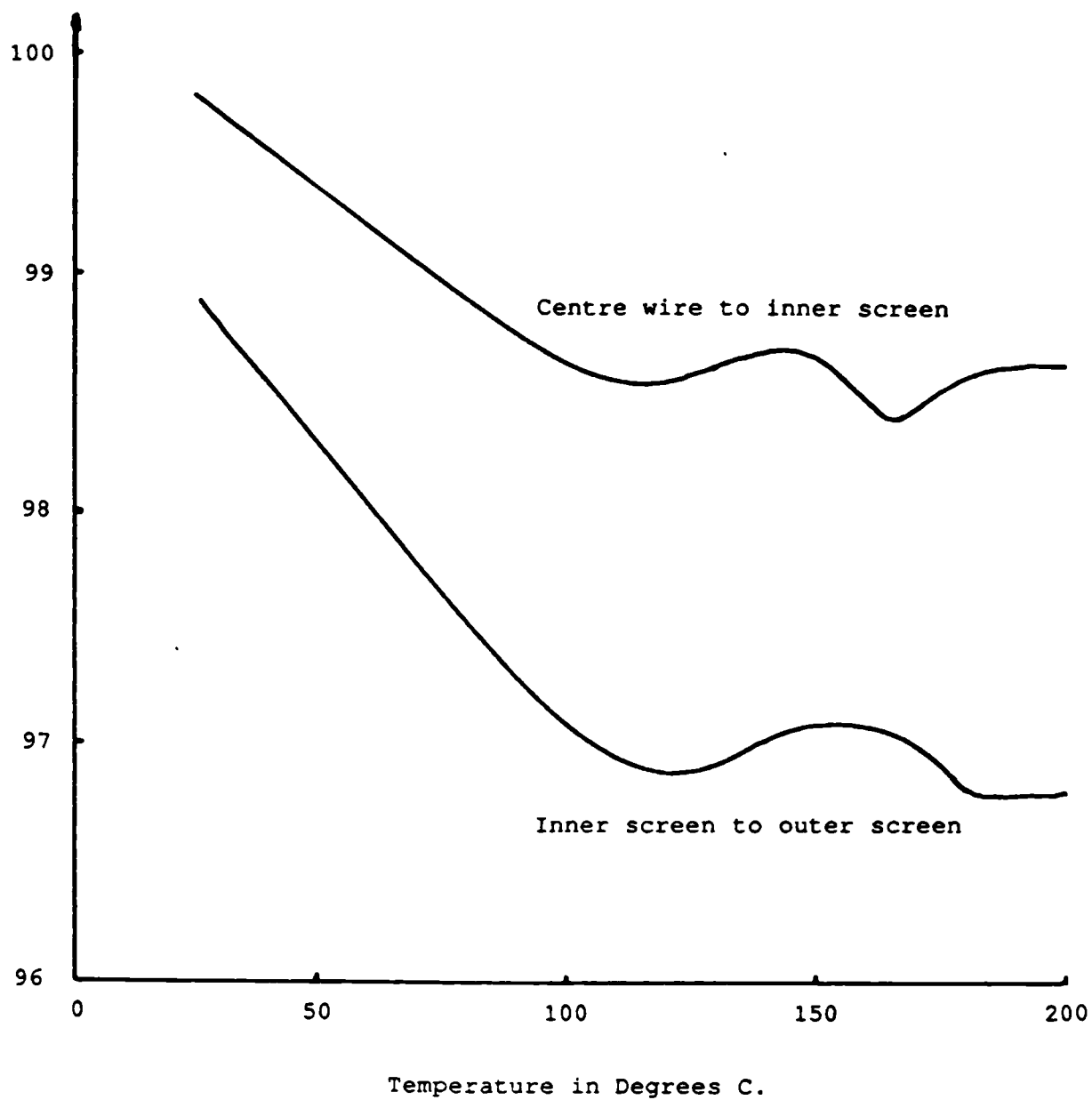


Figure 4.13 Capacitance of PTFE Insulated Double-Screened Cable v Temperature.

cable was considerably more stable and showed a decrease in capacitance of some 2% between room temperature and the maximum rated temperature of the cable of 200 degrees C.

Many designs of unity gain amplifiers were evaluated but by far the most successful design resulted from the use of a National Semiconductor amplifier supplied in a T03 package (LH0002H). The criteria used for judging the efficacy of the designs were the deviation of the voltage gain and phase shift across the amplifier from values of 1 and 0 degrees respectively, when driving a reactive load at a frequency of 10 MHz. An efficiency in the order of 99% in driving the guard screen is needed in order to reduce the varying component of the probe shunt capacitance to a sufficiently small value (< 2 pF) such that the afc circuit can maintain control of the carrier frequency. A reactive load, represented by a maximum of a 180 pF capacitor, when driven by the LH0002H amplifier at a frequency of 10 MHz., resulted typically in a voltage gain of 0.998 and a phase lag of 7 degrees when comparing the amplifier output with the input signal i.e. an efficiency of 99% ($0.998 \cos 7^\circ \approx 100\%$). Effectively, in a driven screen or guarded circuit configuration, the 180 pF load has been reduced to only 1.8 pF.

The effective maximum reactive load of 180 pF can be expressed in terms of lengths of either alumina or PTFE insulated double screened cable. For the alumina cable, the high temperature situation is the one considered where the effective capacitance is greater than at room temperature. From Figure 4.12 it can be seen that at a temperature of 600 degrees C. a cable length of only 180mm represents a capacitance of 180 pF

between the inner and outer screens. For the PTFE insulated cable the maximum length extends to 1800mm.

4.2.5 Line Driver Amplifier.

In order to transmit the 10 MHz. signal from the measuring probe to a demodulator which may be some 100 to 150 meters distant, a matched transmission line must be used. this is to minimise unwanted radiation of the signal and ensure maximum power transfer. An additional LH0002H amplifier was selected for this function with an output impedance set to a nominal 50 ohms thus enabling it to drive a standard r.f.coaxial transmission line.

The circuit of the complete modulator comprising oscillator, voltage regulator, guard circuit amplifier and line driver amplifier is shown in Figure 4.14.

4.3.0 Ground Station.

The ground station is located remotely from the measuring probe and contains all the necessary power supplies for the complete measuring system, the demodulator and the automatic frequency control (AFC.) circuitry which is required to compensate the oscillator for local temperature changes.

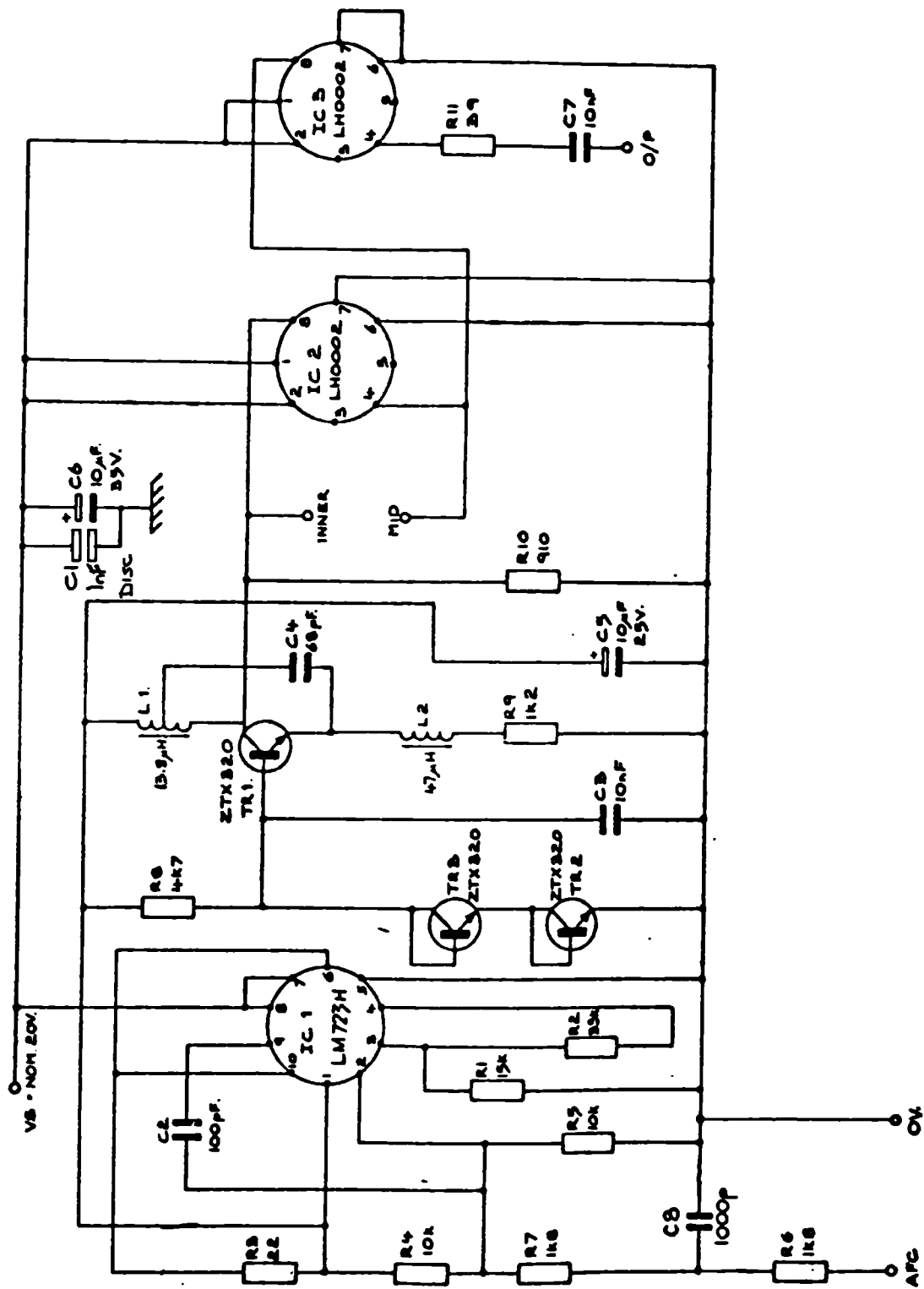
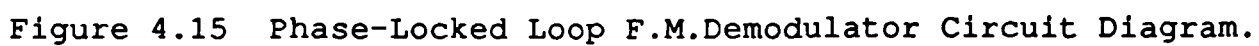


Figure 4.14 Measuring Probe - Modulator Circuit Diagram.

4.3.1 Frequency Demodulator.

The demodulator design is based on the use of a monolithic phase-locked loop integrated circuit, the XR-215, manufactured by Exar Integrated Systems Inc. The circuit, as developed for this application which requires a greater bandwidth than that specified for fm broadcast use, is shown in Figure 4.15 with the recommended component values (Ref.38). The frequency response of the demodulator is shown plotted in Figure 4.16. This gives adequate response for blade passing frequencies up to 20 kHz., assuming that harmonics of blade passing up to the fifth need to be resolved ie a flat response to a frequency in excess of 100 kHz. The need for a demodulator frequency response that encompassed the fifth harmonic of the blade passing frequency was predicted from purely geometric consideration of the probe field pattern and typical gas turbine blade thickness to gap ratios. During subsequent testing of the prototype clearance measuring system spectral analysis of the blade passing signals confirmed this prediction.



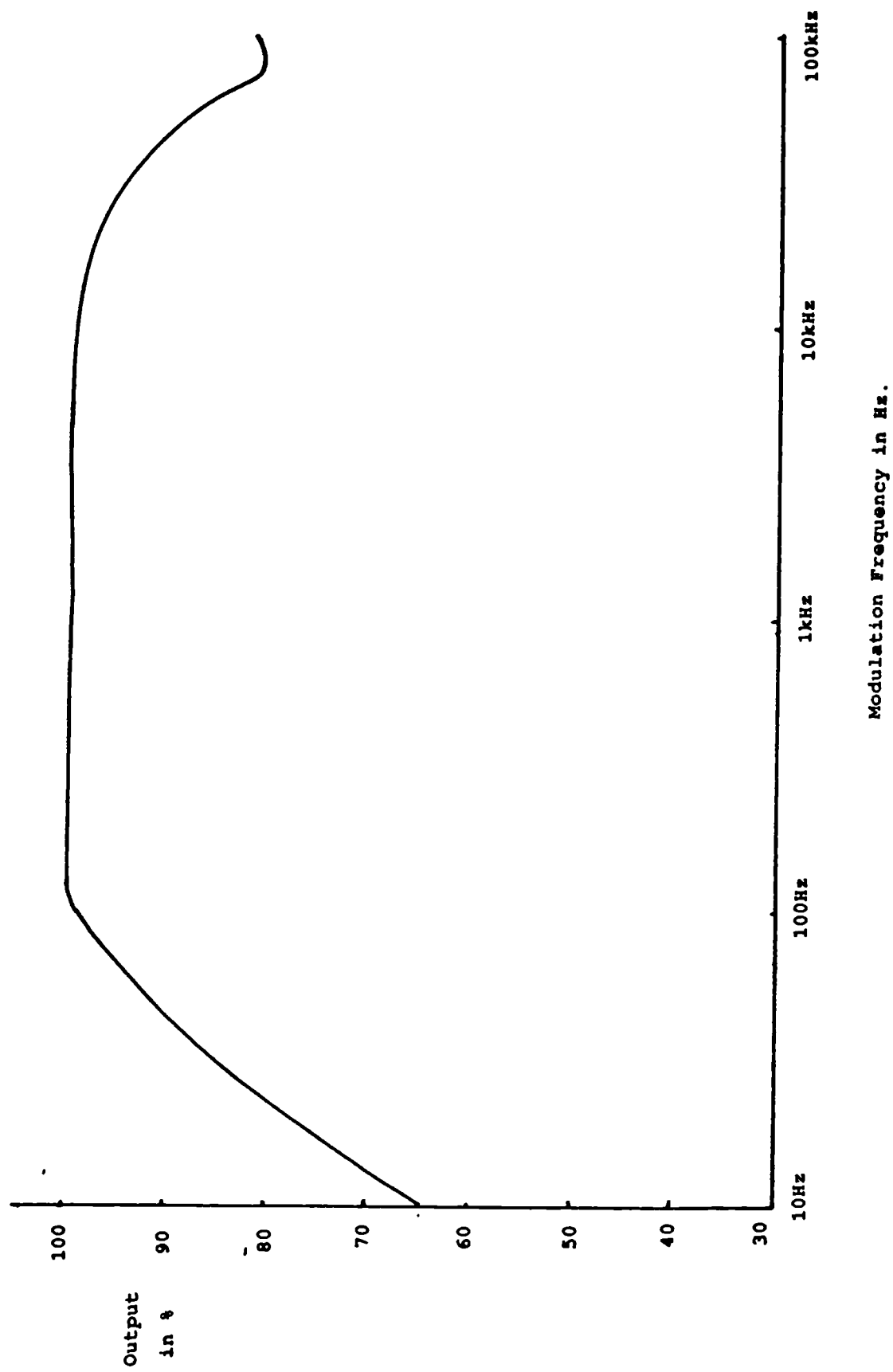


Figure 4.16 F.M.Demodulator Frequency Response.

4.3.2 A.F.C. Control Amplifier.

The function of the A.F.C. amplifier is threefold:-

- a) To compare with a reference voltage level the average voltage output of the demodulator. This voltage is linearly related to the measuring probe oscillator center frequency.
- b) To remove the high frequency blade passing signal components from the demodulator output by means of a low pass filter.
- c) To amplify (by approximately 20 dB) the resultant low frequency component of the demodulator output which results from temperature-induced frequency changes in the measuring probe oscillator. This signal controls the voltage regulator circuit in the measuring probe modulator.

The developed circuit of the afc amplifier is shown in Figure 4.17. Any changes in the measuring probe oscillator center frequency will result in a change in the average dc voltage output of the demodulator. This change in voltage level is conditioned by the A.F.C. amplifier and is fed to the control input of the regulator. The supply voltage to the oscillator circuit is then varied in such a manner as to return the frequency of oscillation to original value.

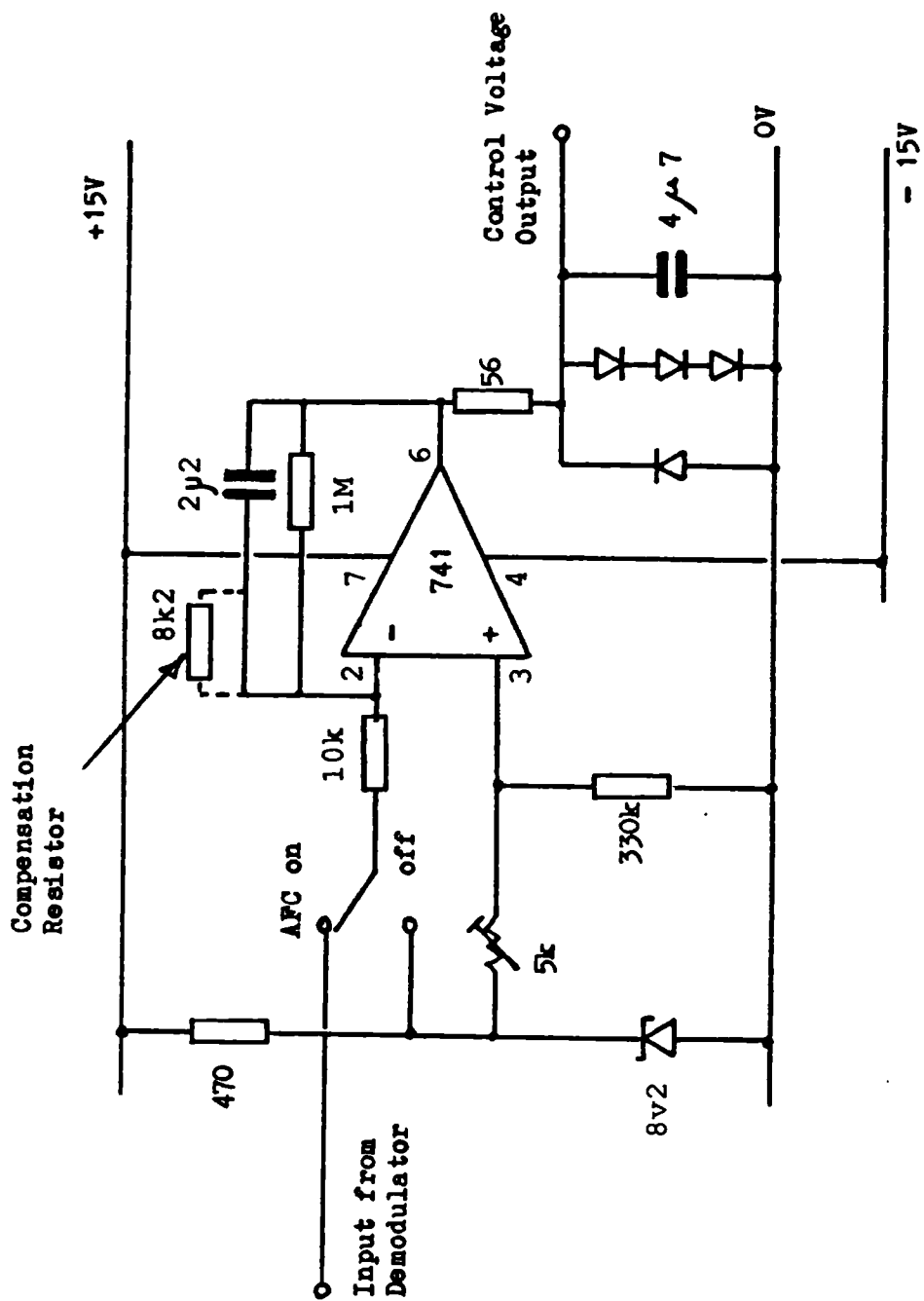


Figure 4.17 A.F.C. Amplifier Circuit.

During the development of the A.F.C.circuit, which is an example of a closed loop control system, it was observed that selection of the frequency control caused a low frequency instability to occur at approximately 10 Hz. This resulted in a spurious output from the clearance system, comparable in amplitude to that of a typical clearance signal.

The system was analysed using a Transfer Function Analyser (Solartron Type JM1172) which enabled the open-loop frequency response of the system to be determined. The results are shown graphically in the form of a Nichols plot in Figure 4.18. Examination of this plot confirms the observed instability at 10 Hz. since the curve intersects the +2.3 dB.locus and passes through the point of instability (0 dB.and -180 degrees). To obtain the desired critically damped response the plot was in effect moved to the right on the chart by means of modelling the loop using a computer program (HYTFRR) to just touch the +2.3 dB. locus by applying phase lead compensation. A single phase lead term, with a break frequency of 8 Hz., was found to provide optimum compensation. A computed Nichols plot of the modified compensated system is shown in Figure 4.19. The lead compensation required to the control loop simply involved the addition of single resistor (shown dotted in Figure 4.17) to the afc amplifier. A plot of the response of the modified compensated circuit is shown in Figure 4.20, and can be seen to compare very well with the predicted response shown in Figure 4.19.

The system with the afc selected now proved to be stable. The response plot shows that 30 dB. of additional gain or 43

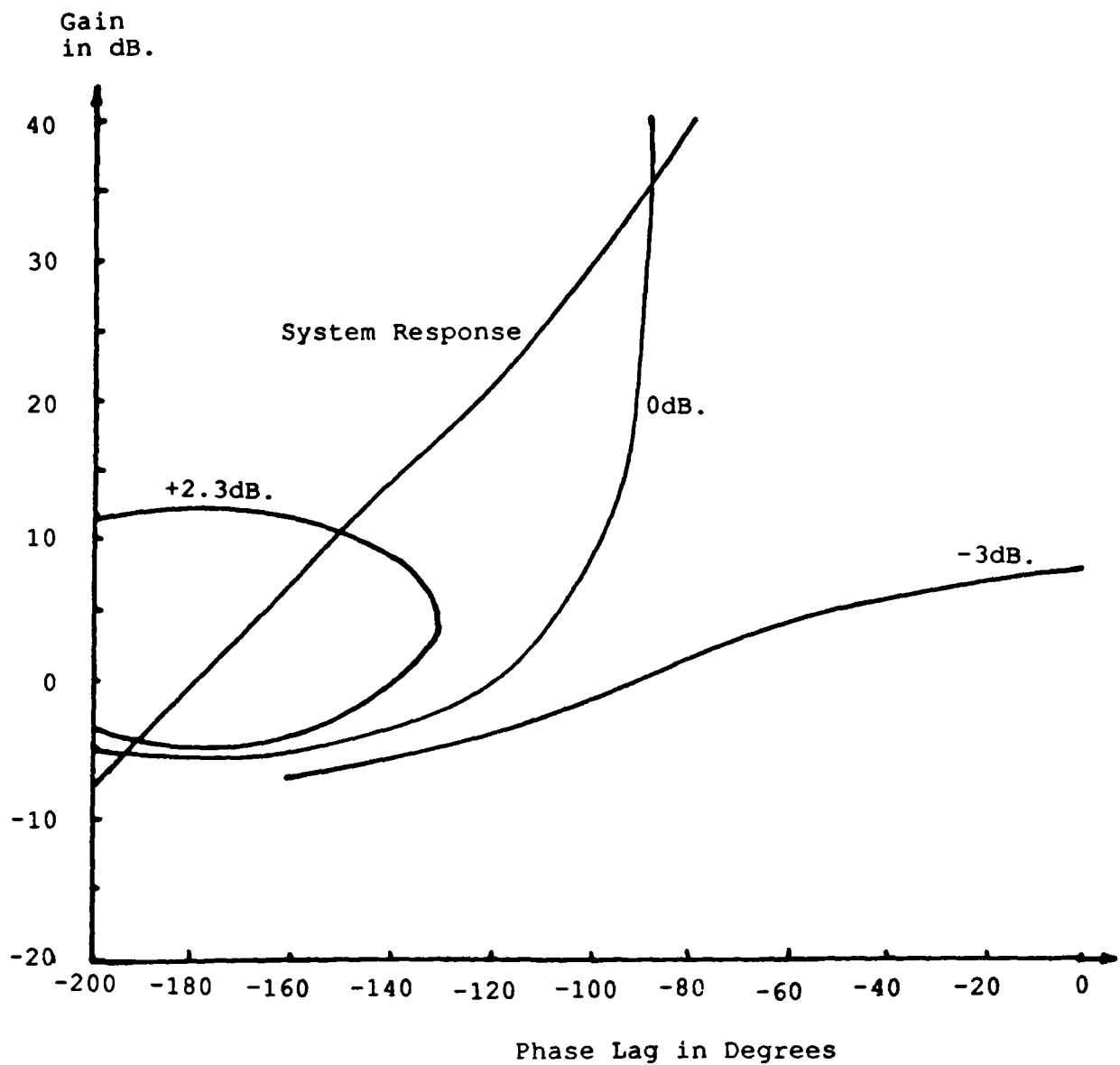


Figure 4.18 Nichols Plot of Unstable System.

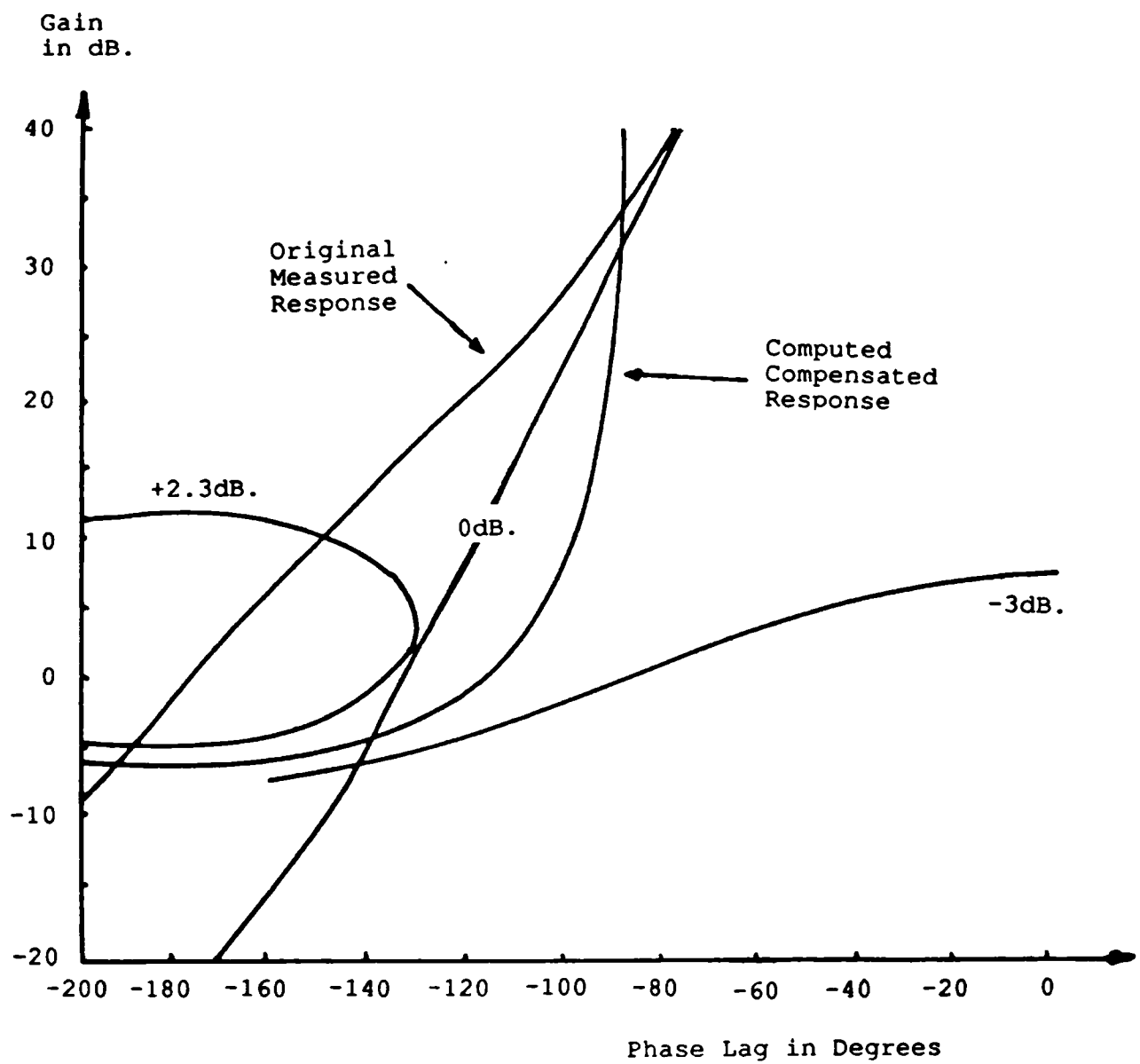


Figure 4.19 Predicted Response of Compensated System.

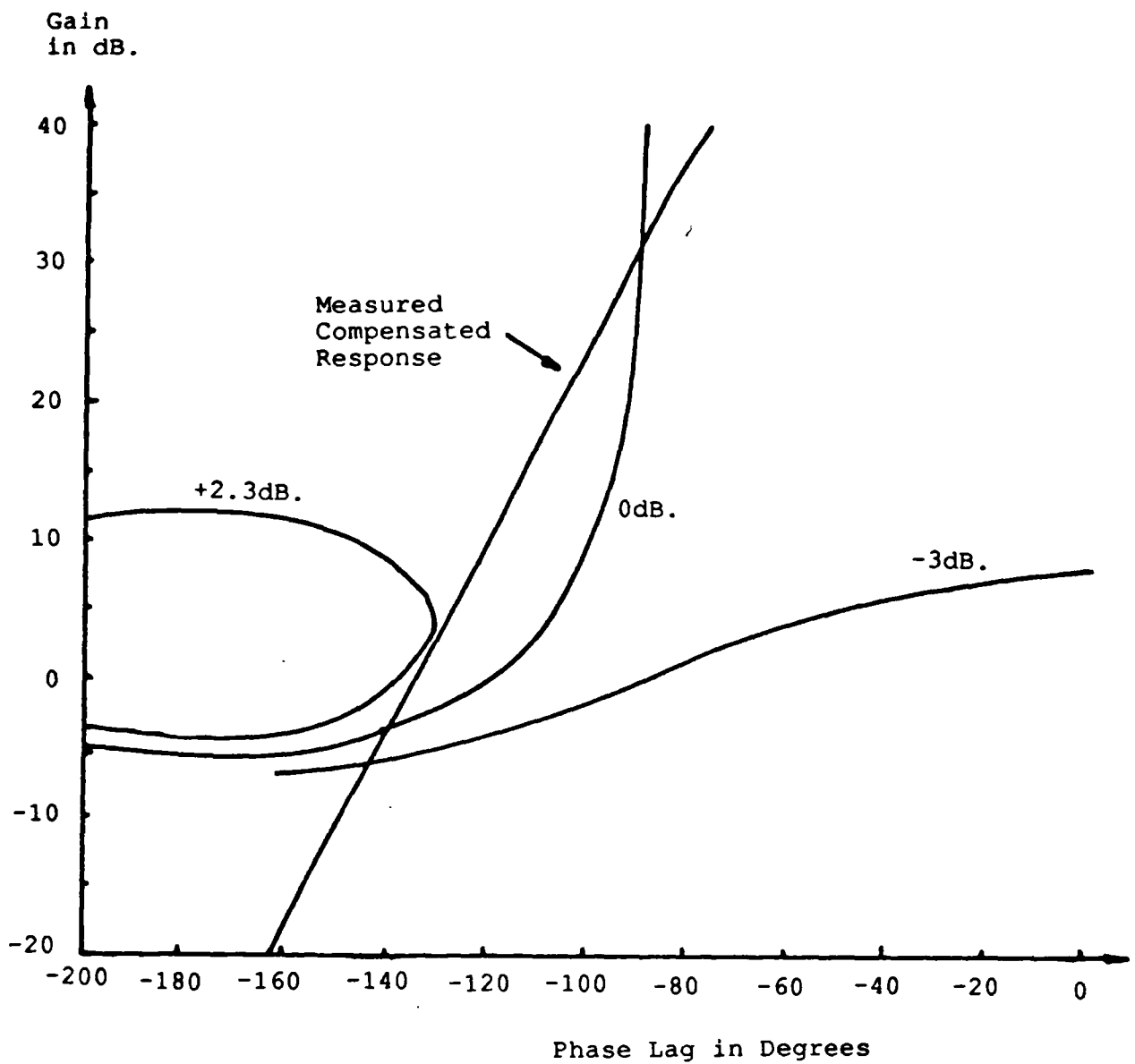
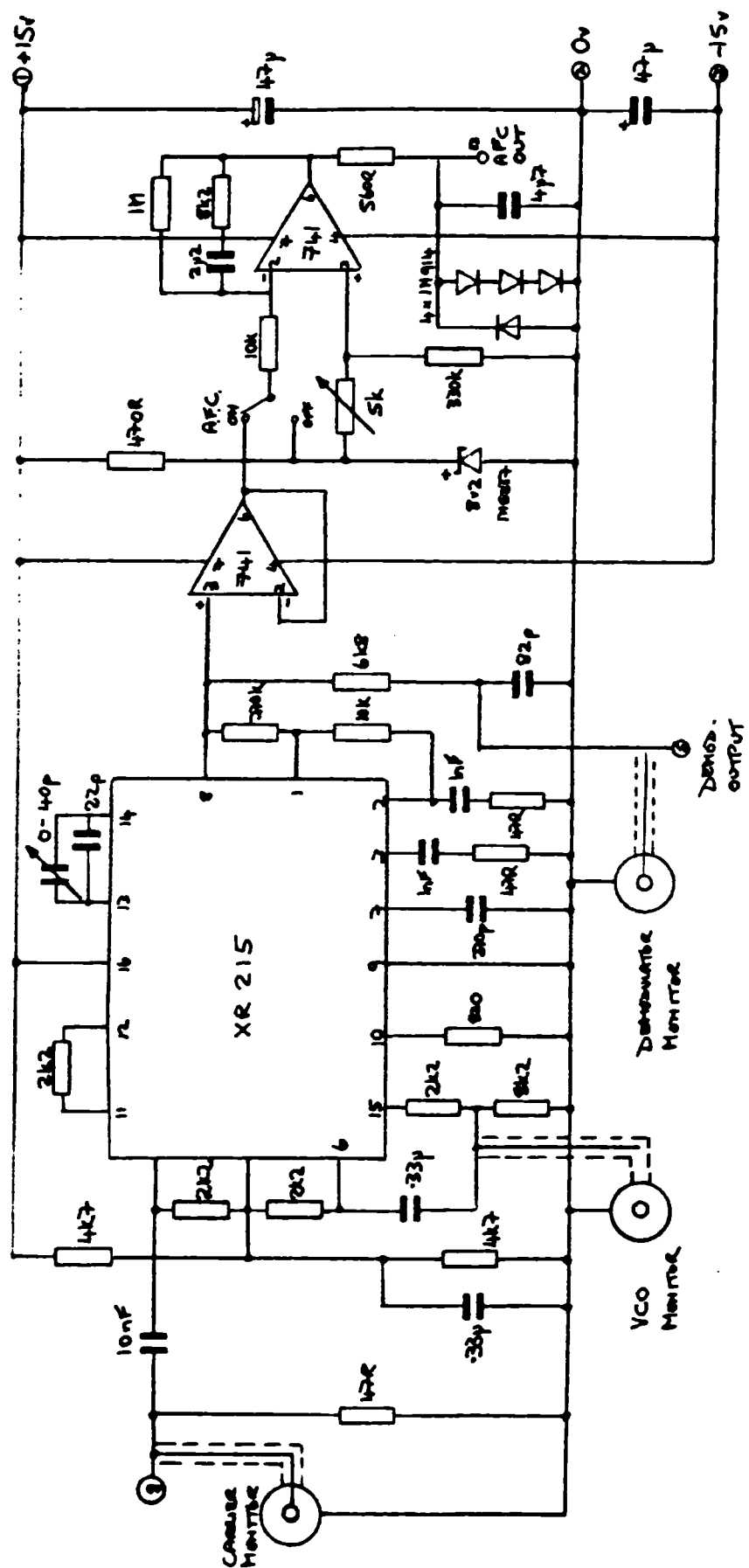


Figure 4.20 Measured Response of Compensated System.

degrees of phase lag would now be required to make the plot pass through the point of instability ie.the circuit has a gain/phase margin of 30 dB.and 46 degrees respectively. A circuit diagram of the developed demodulator/afc amplifier is shown in Figure 4.21.



4.4.0 System Calibration Factors.

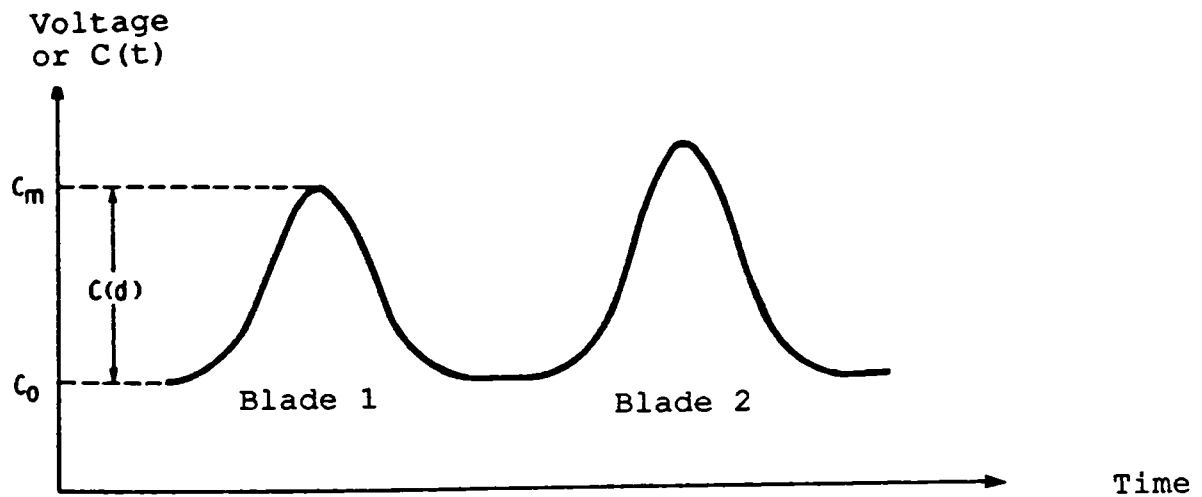
During the development and evaluation of the modulator, and in particular the oscillator circuit, as detailed in Chapter 4.2.0., it became apparent that no two nominally identical circuits performed in exactly the same manner. Such characteristics as the oscillator centre frequency, the deviation in oscillator frequency in response to a defined capacitance change and the oscillator frequency versus supply voltage characteristic, were found to vary from one circuit to another by as much as 10%. A similar variation in performance was observed in the demodulator circuits which were evaluated. These performance variations were due primarily to the variations in component values within the tolerance bands and non-uniformity of characteristics of the semiconductors used.

In addition, the absolute clearance versus system output voltage relationship, ie the system calibration, will not only be determined by the particular measuring probe/demodulator combination, but will also be a function of the geometry of the application. The term "geometry" includes the fundamental physical factors which affect the absolute value of capacitance measured, such as the thickness of the rotor blade tips being measured and the measuring probe sensor electrode area. However, less obviously, the angle of the blade tips to the engine axis , commonly referred to as the blade stagger angle, and the relative spacing of the blades on the rotor, affect the calibration of the capacitance clearance measuring system.

The blade stagger angle and spacing do not affect the peak values of capacitance measured and hence the peak frequency deviation of the oscillator circuit. However, in order to derive a mean value of clearance for a complete stage of rotor blades rather than individual blade clearances, as required in the Measurement Specification (Chapter 1.3.5), the voltage pulses at the output of the demodulator circuit are averaged by using a commercially available R.M.S. converter circuit. A peak picking circuit was evaluated as an alternative to the R.M.S. converter, but was rejected due to its high susceptibility to electrical interference. Hence the form factor of the demodulator output signals directly affects the R.M.S. value measured and the system calibration. The effect of changes of blade stagger angle and blade spacing are now considered in a theoretical manner quantitatively and the predictions tested experimentally.

4.4.1 Blade Spacing Factor.

The output of the basic demodulator is a series of voltage pulses, each pulse corresponding to the passage of a blade tip past the sensor electrode. Figure 4.22 shows a plot of how the capacitance, and hence the demodulator output voltage, varies whilst two blades pass under the probe tip. It was predicted that the R.M.S. value of this voltage would be proportional to the square root of the mark to space ratio of the blades. Alternatively, for two rotors which were identical, except for the blade mark to space ratio, the system output voltage at a fixed clearance for the two rotors could be expressed by the relationship:-



Where:- C_m = Capacitance with blade 1 under probe
 C_0 = Capacitance with no blade under probe
 $C(d) = C_m - C_0$
 = Change in measured capacitance caused
 by passage of blade 1 past probe

Figure 4.22 Capacitance v Time Plot For Two Blades To Pass Under Probe Tip.

$$\frac{\text{R.M.S. O/P1}}{\text{R.M.S. O/P2}} = \sqrt{\frac{\text{Mark:Space1}}{\text{Mark:Space2}}} \dots\dots\dots 13)$$

To verify this predicted relationship a small electrically driven spinning rig was fabricated, the rotor of which is shown in Figure 4.23. The rotor featured a maximum of 16 "pseudo" blades, the stagger angle of each being continuously variable between 0 and 90 degrees. The "blades" could also be totally removed from the rotor disc, thus enabling various blade spacings to be generated.

The results of spinning the rotor at a fixed distance of 1mm from a measuring probe whilst increasing the numbers of blades from 2 to 16 in increments of 2 (in order to preserve the dynamic balance of the rotor) are shown plotted in Figure 4.24.

It can be seen that although a straight line is generated as predicted for a plot of R.M.S. voltage against the square root of the mark to space ratio, there is an offset of approximately 0.27 volts when the mark to space ratio is zero. It was appreciated at this stage that the relationship between the R.M.S. output and the blade spacings was more accurately expressed thus:-

$$\text{R.M.S. O/P} \propto \sqrt{\text{Mark:Mark+Space}}$$

$$\propto \sqrt{\text{Mark:Pitch}} \dots\dots\dots 14)$$

Figure 4.25 presents the results of the experiment replotted

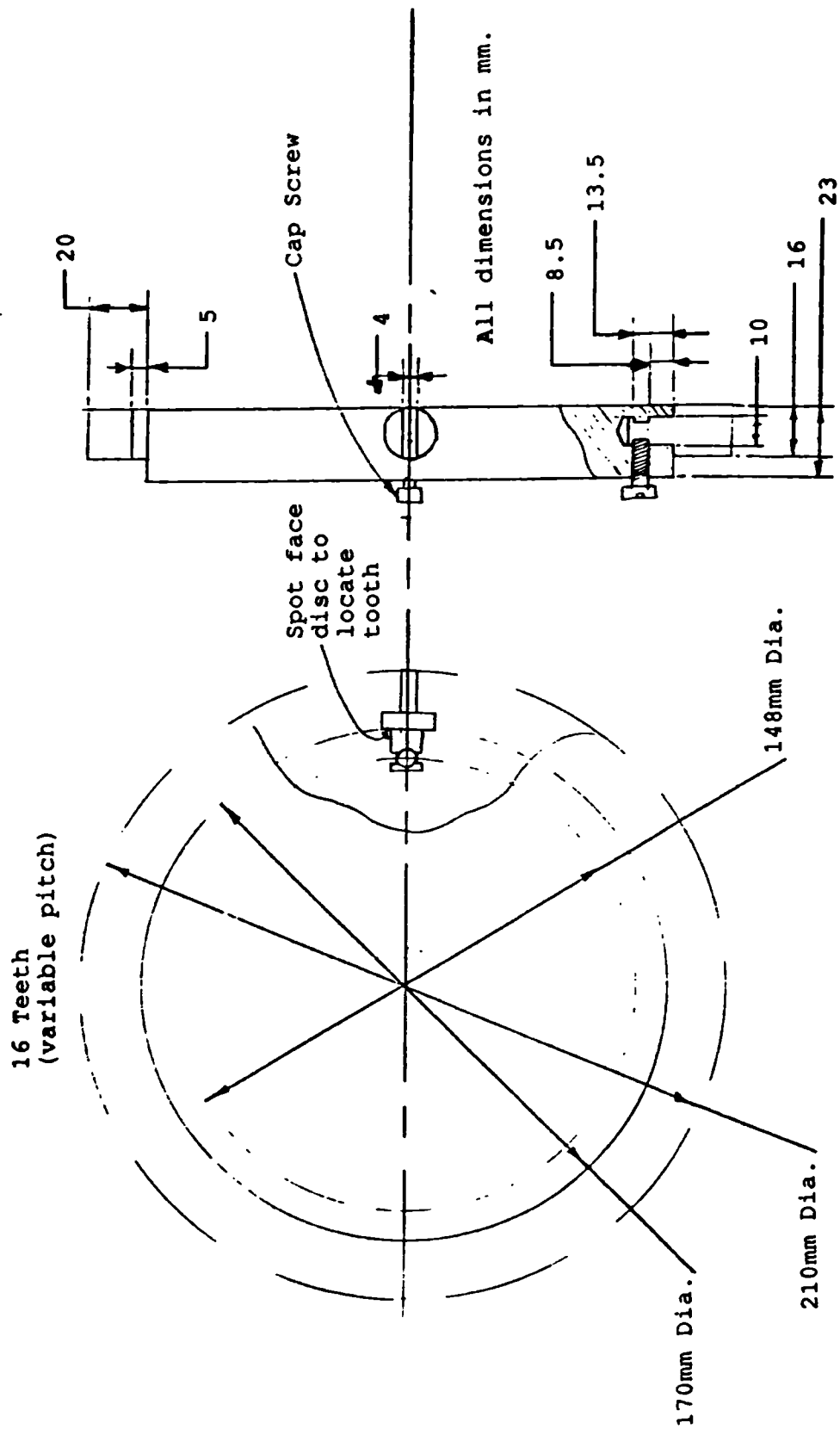


Figure 4.23 Spinning Rig Variable Pitch Rotor.

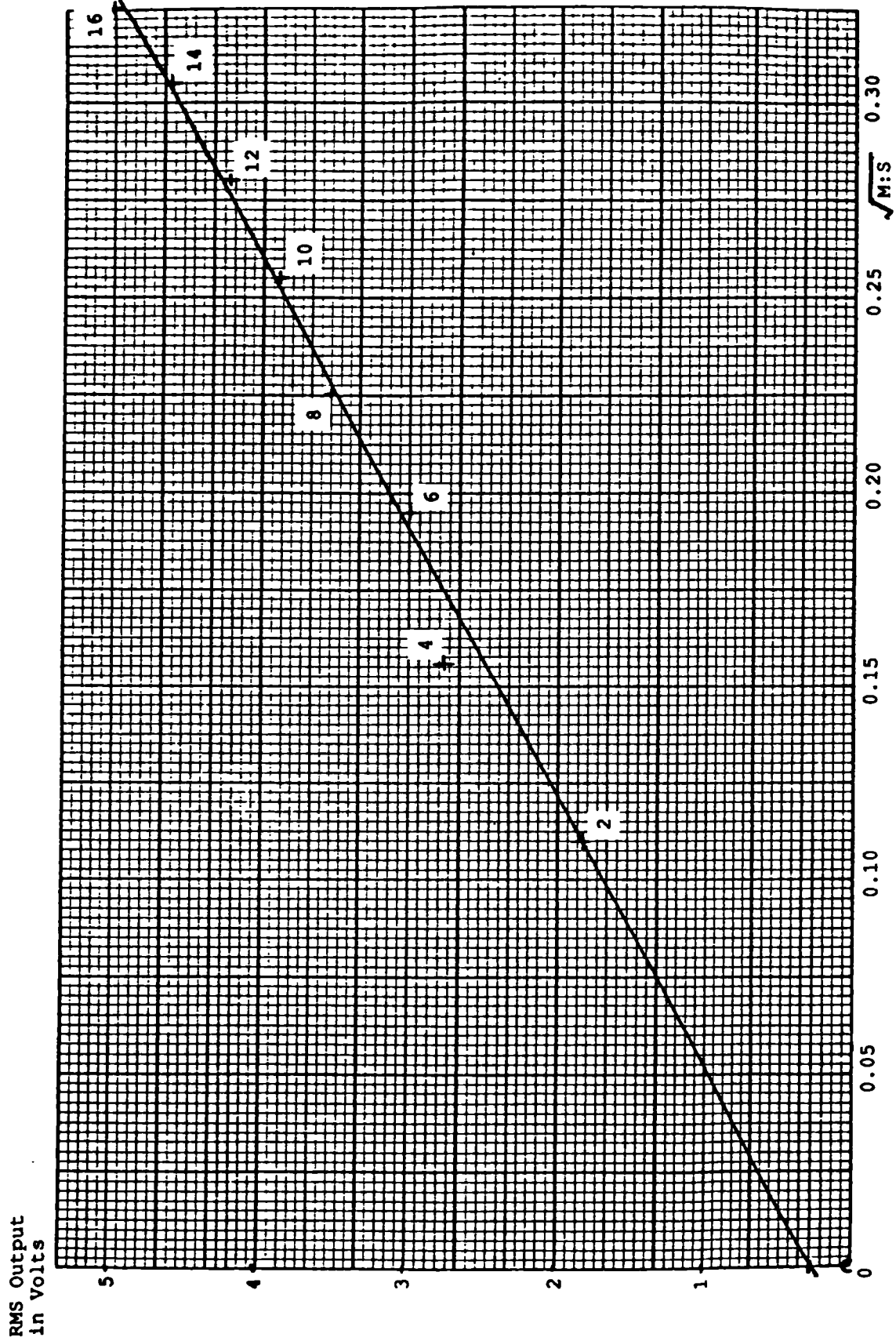


Figure 4.24 Plot of R.M.S. Output v Square Root of Mark:Space Ratio.

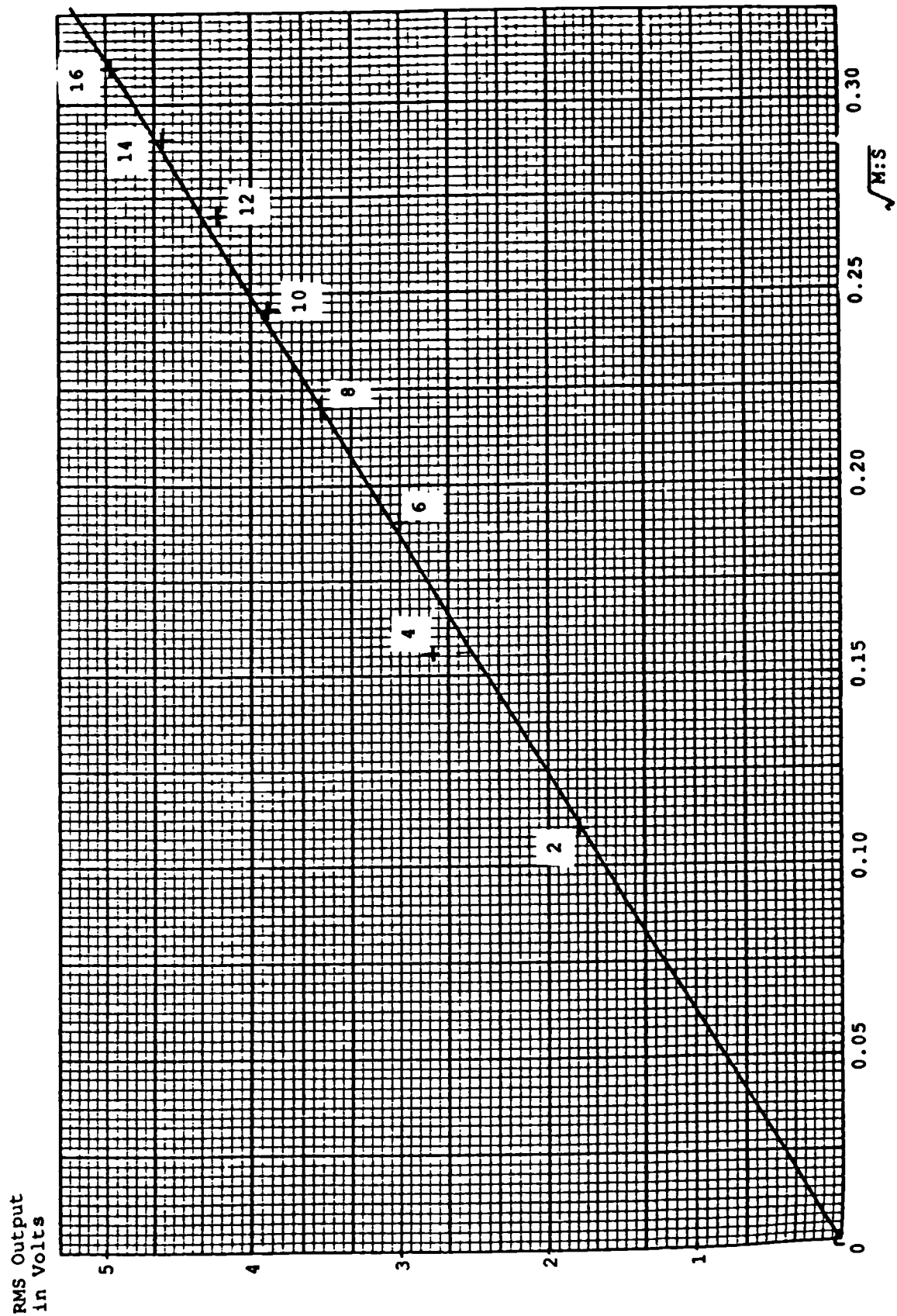


Figure 4.25 Plot of R.M.S. Output v Square Root of Mark:Pitch Ratio.

against the square root of mark to pitch ratio. The straight line now passes through the origin which confirms experimentally the correction to the prediction which links the R.M.S.output to the mark to pitch ratio.

4.4.2 Blade Stagger Angle Factor.

Figure 4.26 shows schematically the geometric effects caused by varying the blade stagger angle from 0 degrees to θ degrees. Increasing the stagger angle from 0 to θ degrees effectively increases the mark to pitch ratio:-

$$\frac{M_{\theta}}{P} = \frac{M_0}{P} \cdot \frac{1}{\cos \theta} \dots\dots\dots 15)$$

As:-

$$\text{R.M.S. O/P} \propto \sqrt{M:P} \quad (\text{from chapter 4.4.1})$$

And:-

$$\cos \theta = \frac{M_0/P}{M_{\theta}/P} \quad \text{from equation 15)}$$

Hence:-

$$\cos \theta = \left[\frac{\text{R.M.S. O/P}_0}{\text{R.M.S. O/P}_{\theta}} \right]^2 \dots\dots\dots 16)$$

In order to test this relationship, the small spinning rig was used with 8 blades set at a stagger angle of zero degrees. The R.M.S. voltage output of the clearance system was noted against the absolute clearance over a range of 0.25mm to

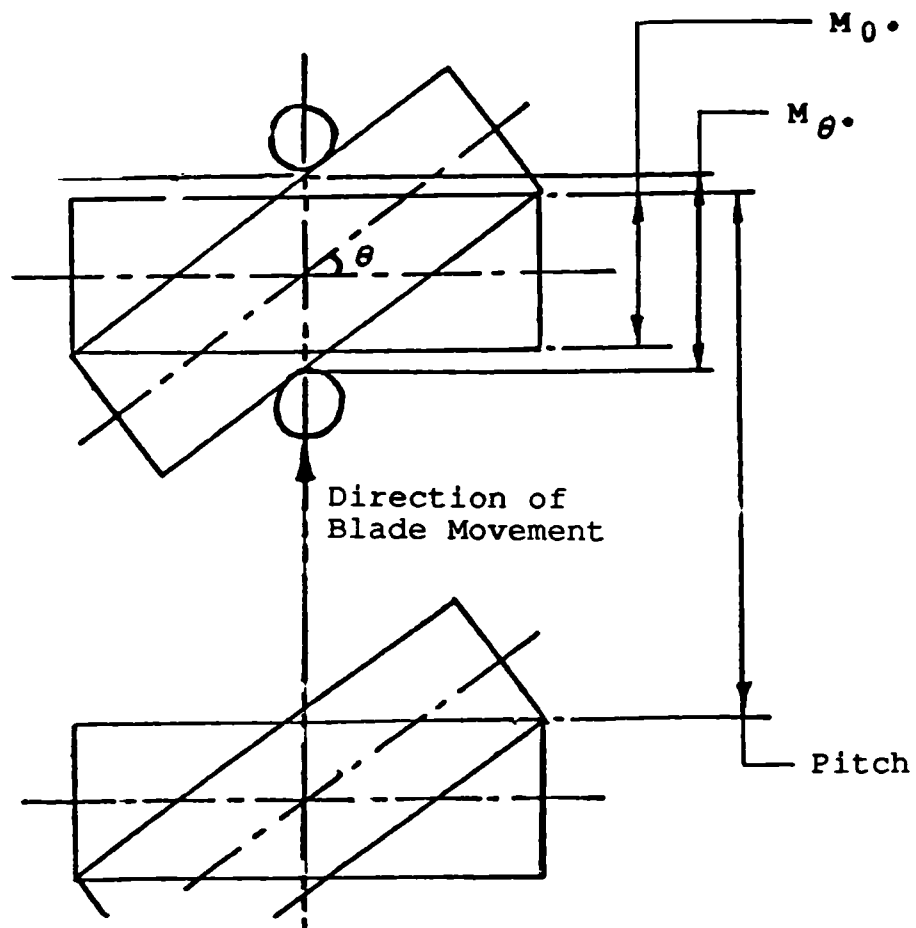


Figure 4.26 Blade Stagger Angle Effect on Mark:Pitch Ratio.

2.25mm. This experiment was repeated after the stagger angle of each blade had been reset to 45 degrees. The test results obtained for the two blade angles were then plotted on one graph and are shown in Figure 4.27. Included on the graph is a third line which corresponds to the predicted output from the clearance system for a blade stagger angle of 45 degrees based on the derived relationship between stagger angle and the system R.M.S. voltage outputs at any angle and zero (equation 16).

Examination of the test and predicted results shown in Figure 4.27 shows that the measured output of the system appears to be less than the predicted output at a clearance. The error is, on average, equivalent to a clearance offset of approximately 0.025mm. This apparent anomaly can be explained by consideration of the geometry created by simply changing the blade stagger angles. Figure 4.28 shows schematically a plan and elevation of an individual blade. Changing the stagger angle of the blade effectively increases the radius of revolution of the whole rotor. At a blade stagger angle of zero, the zero datum clearance for the experiment is taken from the center of the blades. At any other blade stagger angle, apart from zero, the zero datum clearance is taken from either the leading or trailing edges of the blades, as they have now moved to a greater radius than the blade centres. For the experimental results plotted in Figure 4.27 where $\theta = 45$ degrees, blade thickness, " $2t$ " = 4mm and the radius of the rotor, " r " = 105mm, the correction factor Δr , as derived in Figure 4.28, is +0.002mm. This correction factor when added to the measured results for a blade stagger angle of 45 degrees,

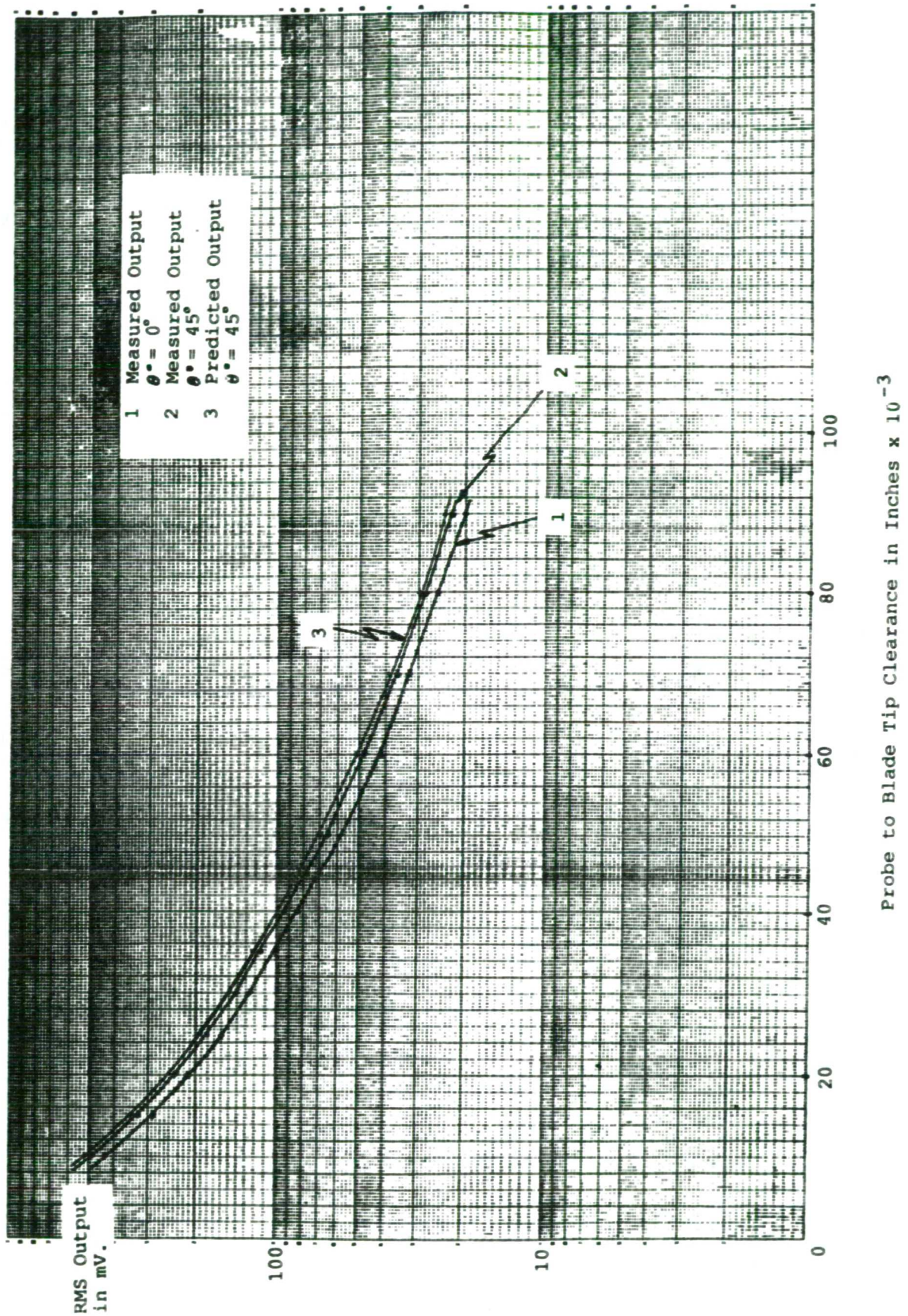
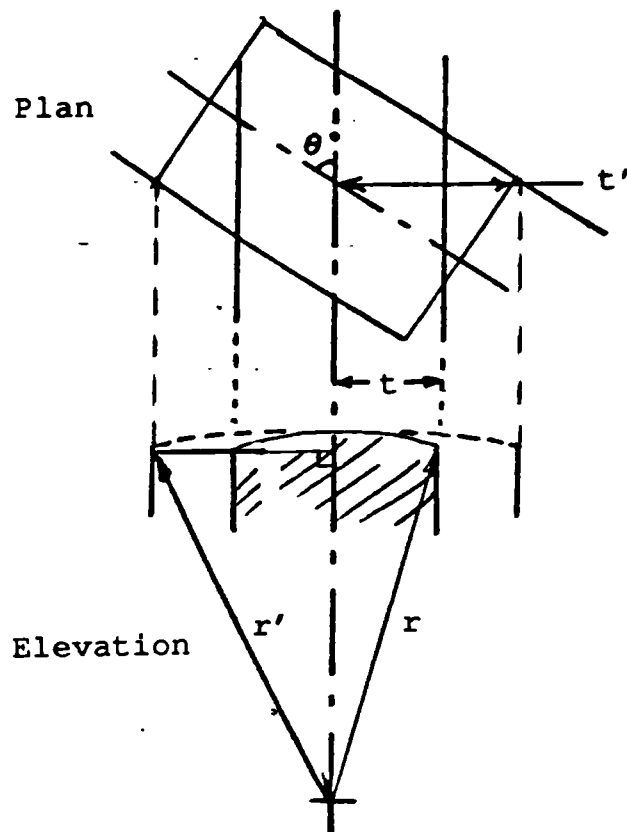


Figure 4.27 Measured and Predicted R.M.S. Output v Clearance Characteristics for Different Blade Stagger Angles.

ensures a near perfect match between the measured and predicted characteristics.

It is thus concluded that the geometric factors which affect the tip clearance system calibration have been satisfactorily explained and quantified.



$$\begin{aligned}
 r'^2 &= (r^2 - t^2) + t'^2 \\
 &= r^2 - t^2 + t^2 / \cos^2 \theta \\
 &= r^2 + t^2 \left[\frac{1}{\cos^2 \theta} - 1 \right] \\
 &= r^2 + t^2 \tan^2 \theta \\
 \Delta r &= \sqrt{t^2 \tan^2 \theta + r^2} - r
 \end{aligned}$$

For:- $t = 2\text{mm}$
 $r = 105\text{mm}$
 $\theta = 45 \text{ degrees}$

$$\underline{\underline{\Delta r = 1.9 \times 10^{-3} \text{mm}}}$$

Figure 4.28 Blade Stagger Angle Effect on Effective Rotor Radius.

5.0 PROTOTYPE SYSTEM DESIGN/MANUFACTURE.

5.1.0 Measuring Probe.

The measuring probe is comprised of the sensor which detects the change in capacitance as a rotor blade tip passes the electrode, and the modulator, which converts the capacitance change into a frequency modulated carrier. Electrically the maximum physical separation between the measuring electrode and the modulator is constrained by the electrical drive capability of the guard circuit amplifier, as described in Chapter 4.2.4. This was found to be represented by a reactive load of 180 pico-farads at a nominal carrier frequency of 10 MHz. Translating this capacitance into a length of cable connecting the electrode to the modulator, gave lengths of 180 millimeters and 1.8 meters for readily available alumina and PTFE insulated double screened cables respectively. The small separation between the electrode and the modulator in an application where the cable temperature could exceed 570K, ie where the use of alumina insulation becomes essential, imposes a potentially severe physical constraint on the measuring probe installation. Considerable thought must be given to the provision of a controlled environment for the modulator which, when using military specification components, will have a maximum recommended temperature limitation of 400K. As previously determined in Chapter 1.3.0, the gas adjacent to the probe electrode in an engine high pressure compressor application may reach 810K and 1500K in an engine high pressure turbine.

5.1.1 Measuring Probe - Sensor.

The prototype measuring probe sensor is fabricated using the high temperature brazed alumina ceramic construction as described in Chapter 4.1.0. A schematic diagram of the sensor is shown in Figure 5.1. Figure 5.2 shows the detailed parts used in the fabrication.

5.1.2 Measuring Probe - Modulator.

The developed modulator circuit diagram is shown fully in Figure 4.14 and comprises the r.f. oscillator whose frequency deviation is a function of blade tip clearance, a voltage regulator to vary the supply voltage to the oscillator and hence provide a control of the oscillator frequency, an amplifier to drive the guard electrode circuitry and an amplifier to drive the oscillator frequency signal along a transmission line to the remote demodulator circuit in the groundstation.

The printed circuit design is shown in Figure 5.3 and follows good radio frequency circuit constructional practices ie. use of double-sided copper circuit board, (the circuit being printed on one side and the other left as a ground plane), shortest length component leads and circuit board tracks to minimise stray circuit capacitances and inductances, and power supply tracks decoupled at radio frequencies by ceramic

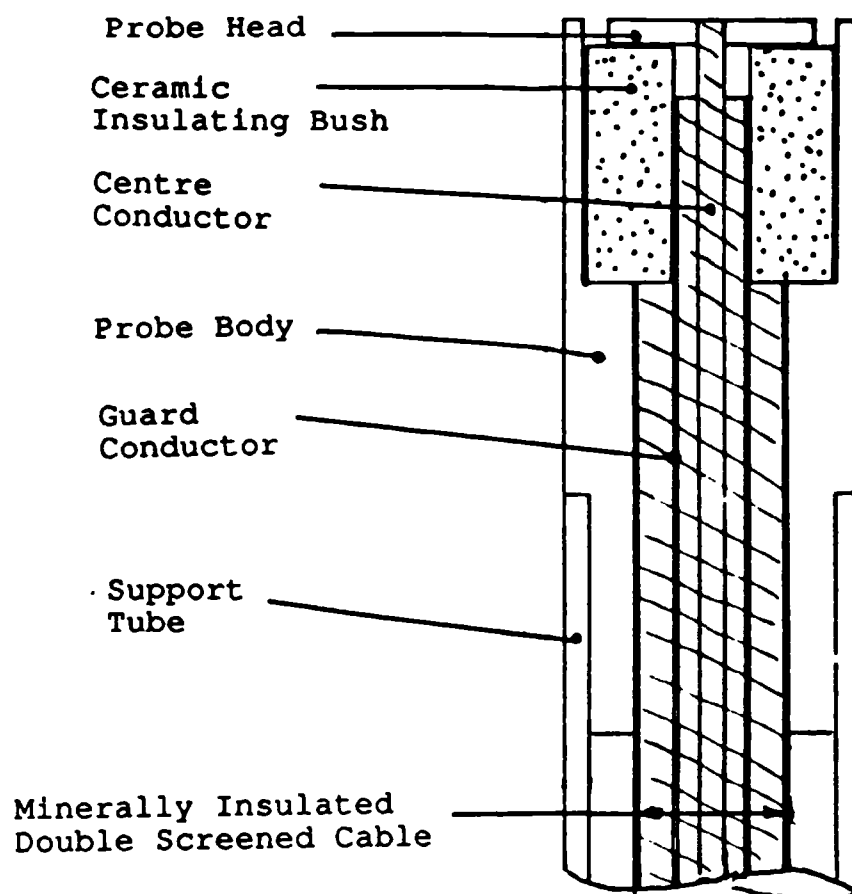


Figure 5.1 Measuring Probe-Sensor:Schematic Diagram.

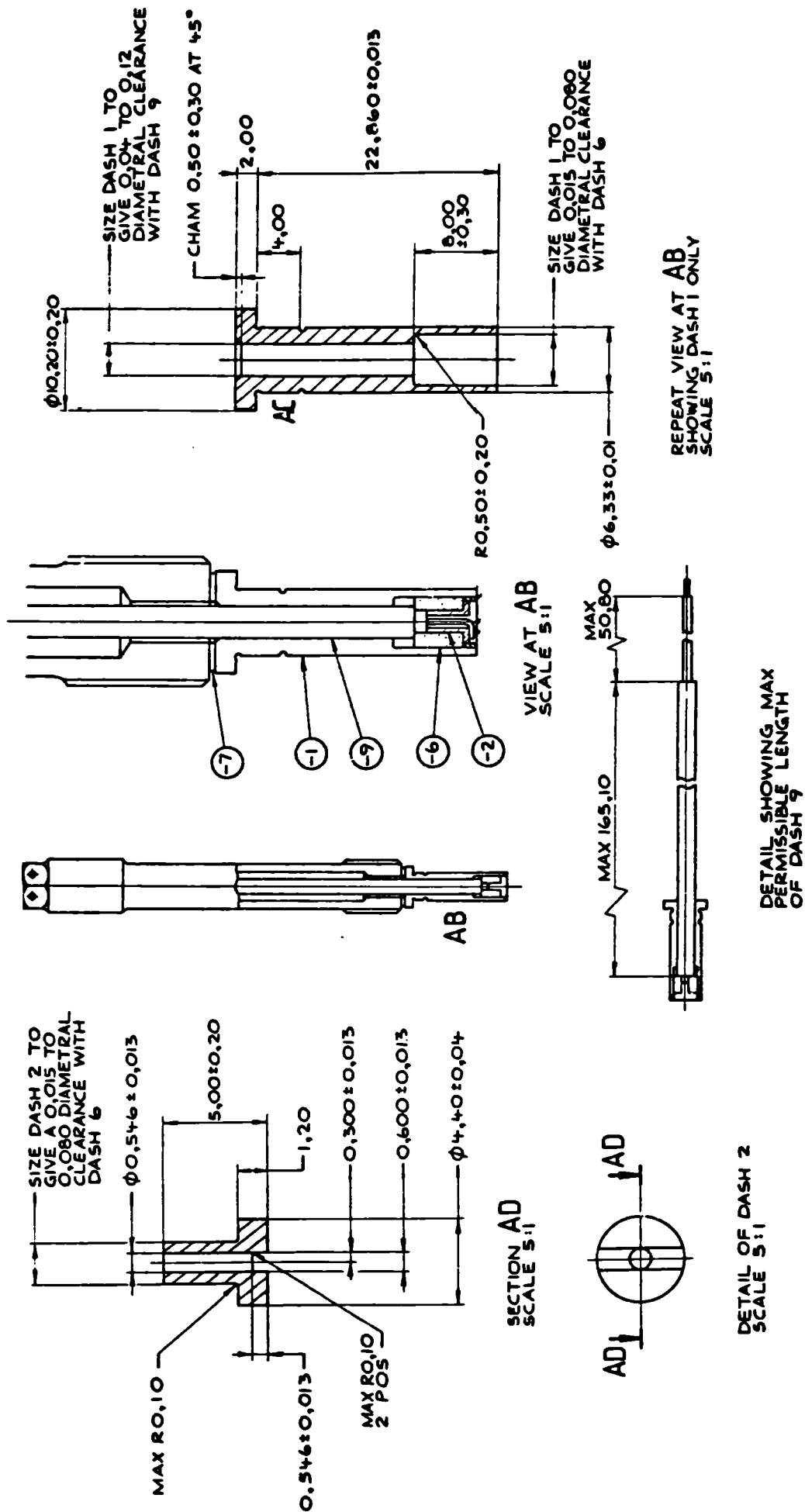


Figure 5.2 Measuring Probe-Sensor: Parts Details.

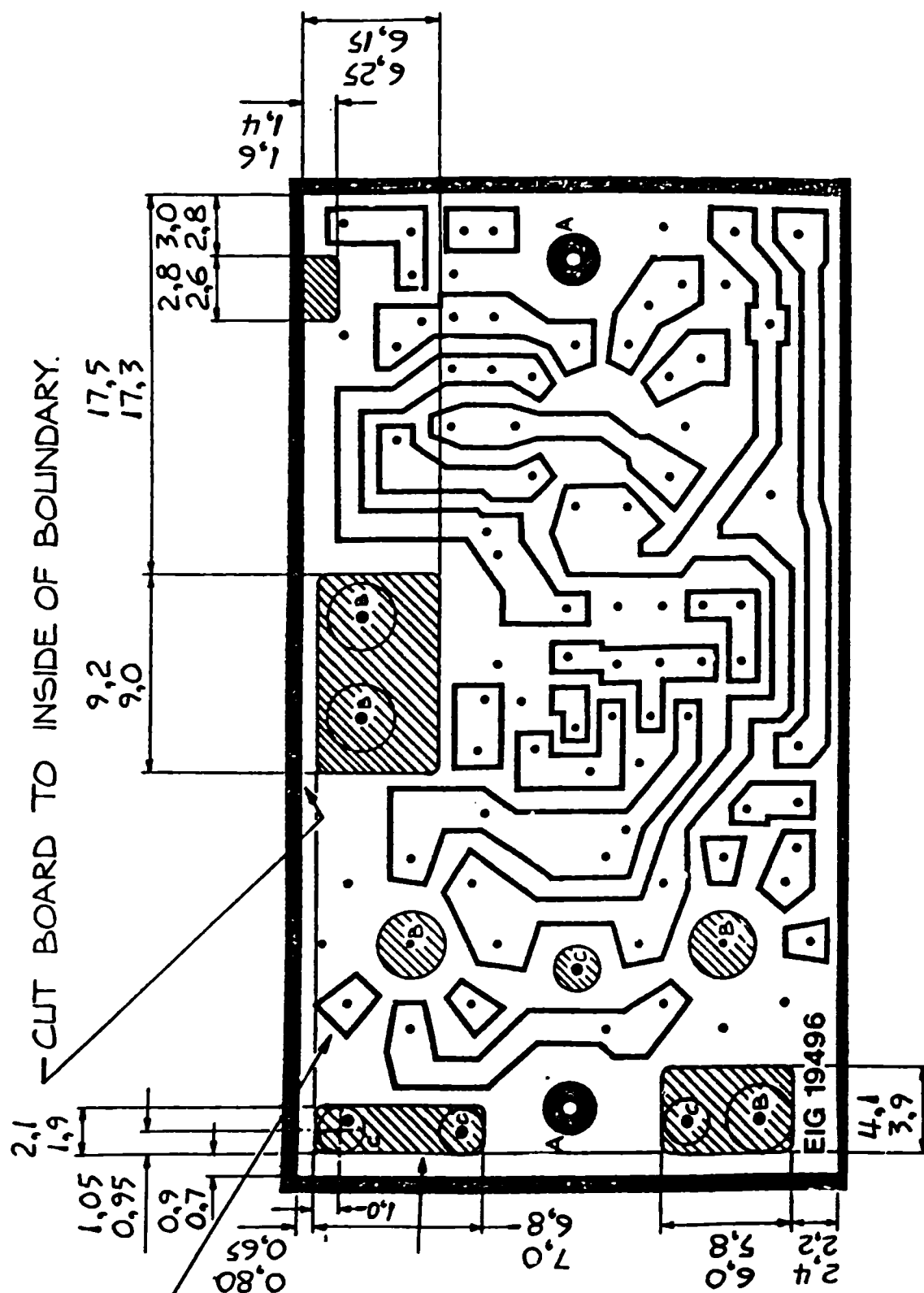


Figure 5.3 Measuring Probe-Modulator: Printed Circuit Design.

capacitors to the earthed ground plane. The arrangement of components on the printed circuit is shown in Figure 5.4 and Figure 5.5 is a photograph of an assembled modulator.

The modulator when tested as shown exhibited a very poor oscillator frequency stability when subjected to mechanical shock or vibration. This deficiency was not totally unexpected following experience gained with experimental f.m. transmitter designs for gas turbine rotating telemetry systems. The solution to the problem lay in potting the entire modulator circuit in a low permittivity, filled epoxy resin material. This had the effect of preventing any relative movement of the modulator components which previously had affected the frequency of oscillation by changing the stray circuit capacitances. The low permittivity potting material ($E < 1.5$) was created by the use of Eccospheres mixed with a Stycast epoxy resin material. By virtue of the potting material having a permittivity close to that of air, the electrical characteristics of the modulator were virtually unaffected by the potting process. Figure 5.6 is a photograph of a potted modulator circuit before assembly into a measuring probe.

5.1.3 Measuring Probe - Assembly.

The first measuring probe design is shown schematically in Figure 5.7. The modulator is housed in the screened enclosure remote from the probe measuring electrode and is connected to it by a length of mineral-insulated double-screened cable.

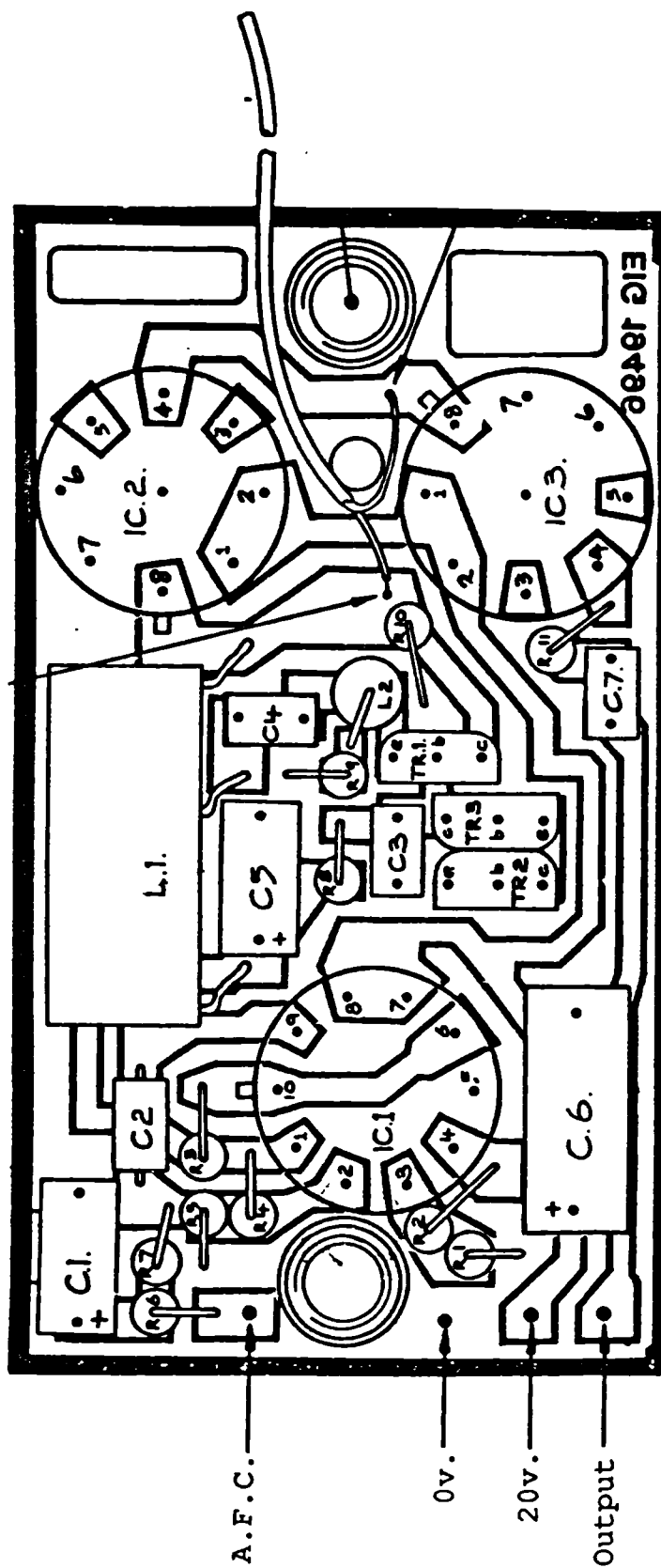


Figure 5.4 Measuring Probe-Modulator: Component Layout.

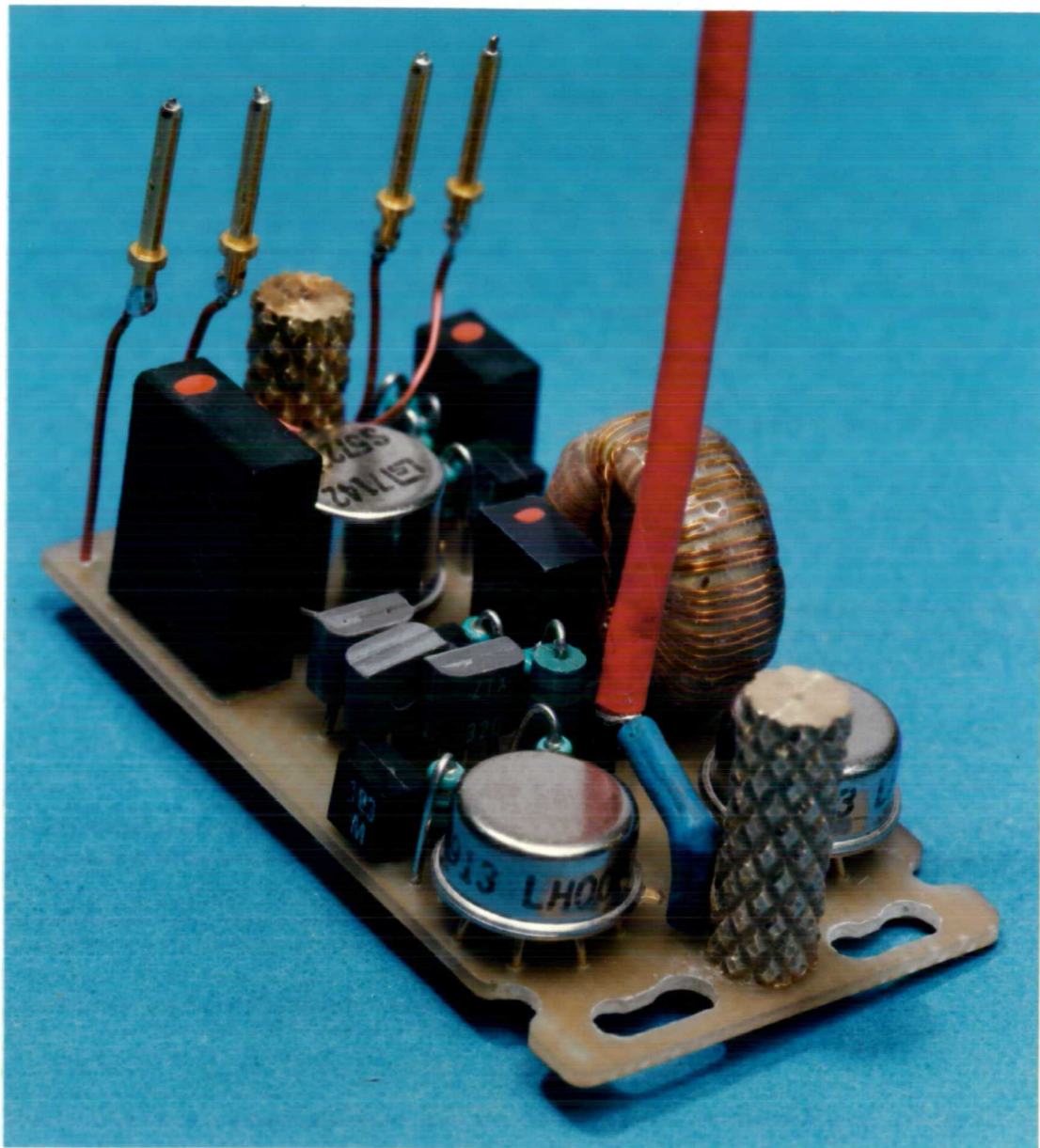


Figure 5.5 Photograph of Assembled Measuring Probe-Modulator.

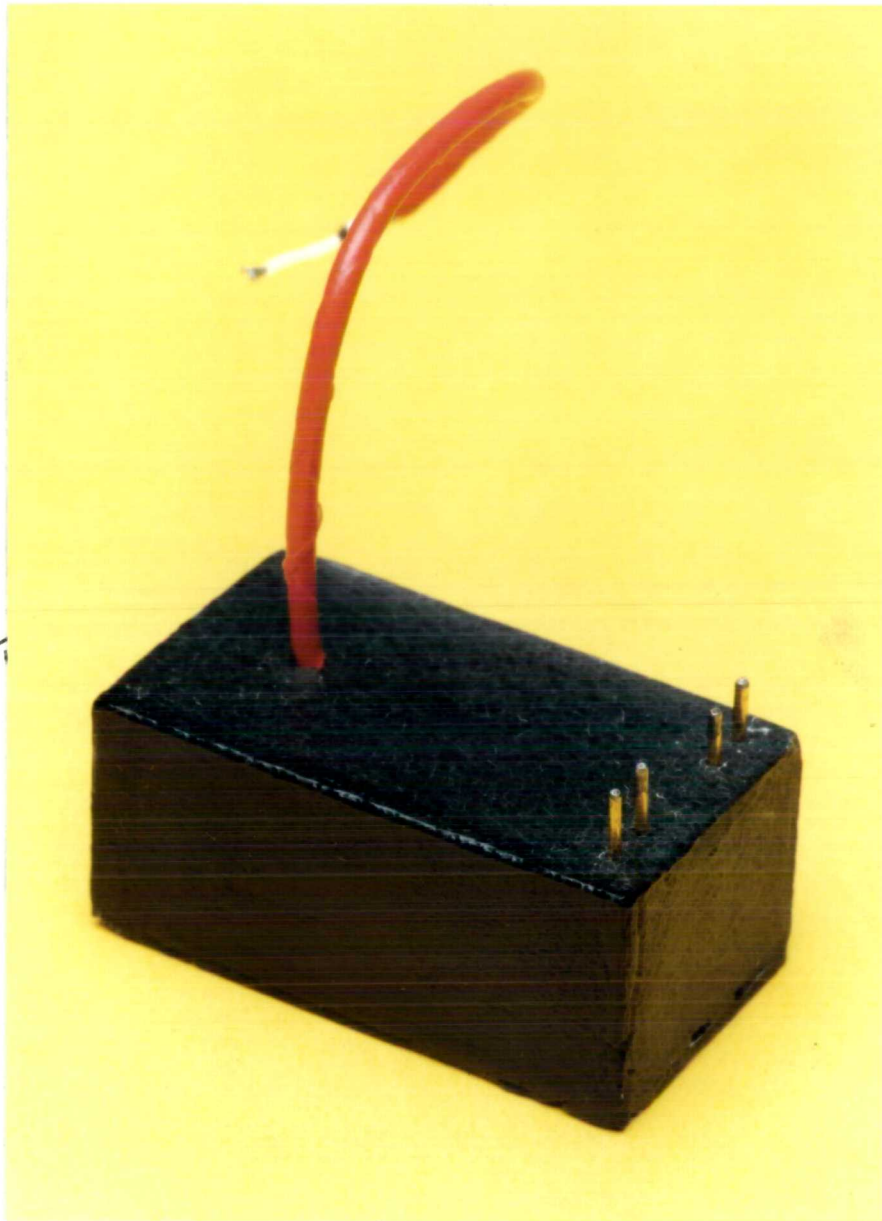


Figure 5.6 Photograph of Potted Modulator.

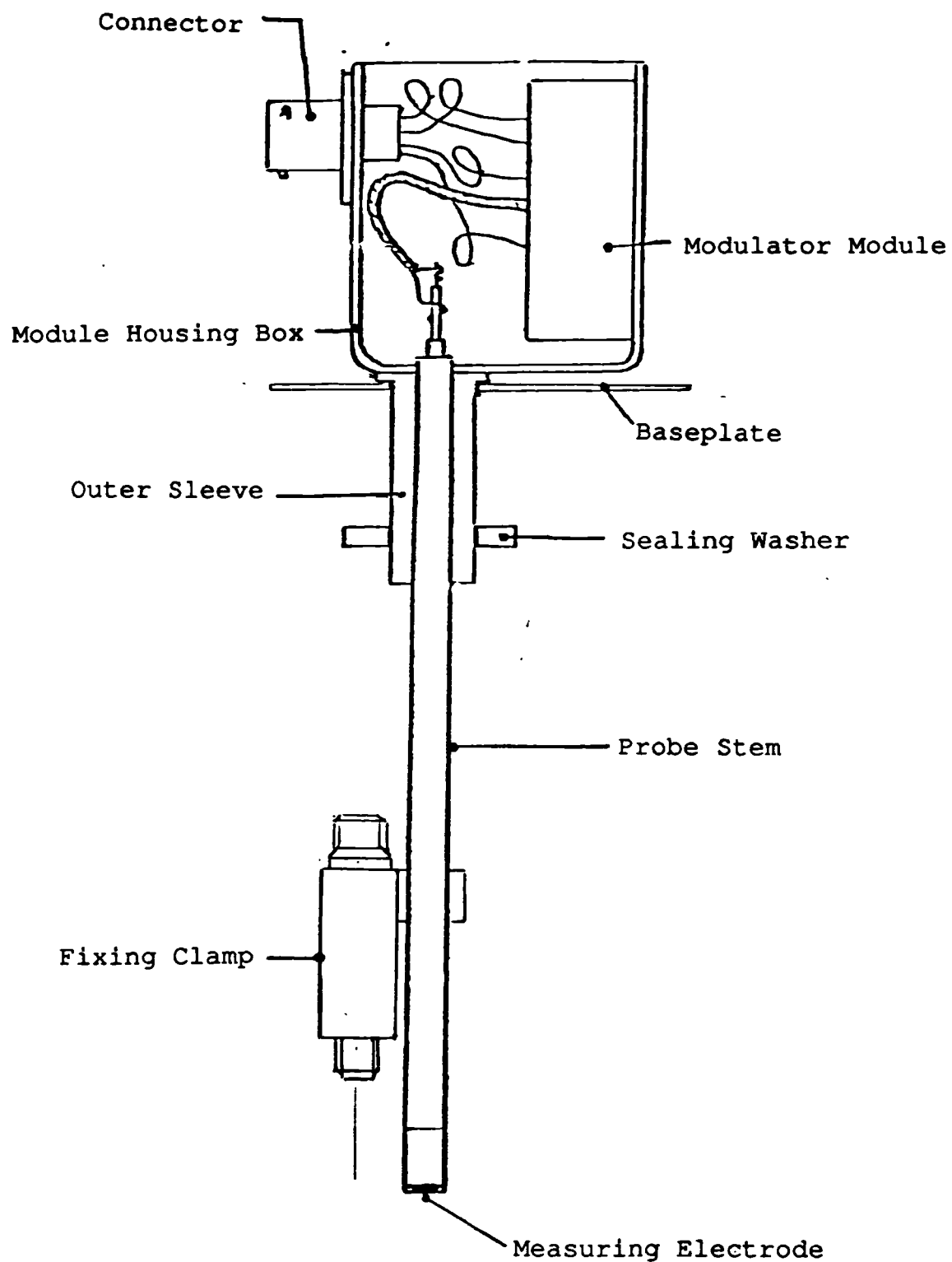


Figure 5.7 Schematic of First Measuring Probe Design.

Mechanically the complete measuring probe is located radially in a gas turbine application at a position as near as practical to where the measurement of rotor blade tip clearance is being made. Thus any movement of the measuring probe electrode, relative to the casing to which it is attached due to material thermal expansion mismatches or temperature gradients, is kept to a minimum. The modulator end of the probe is free to move both radially and axially in order to accommodate probe length changes with temperature and gas loading. This design feature is necessary as, in a typical gas turbine installation, the probe stem must pass through the compressor or turbine pressure casing. Freedom for the probe to move in a radial direction is provided by means of a sealing washer which slides over the outer sleeve on the probe stem. The freedom of movement of the unlocated end of the probe stem in the axial direction is created by the small clearance between the sealing washer and the casing. Photographs of two assembled measuring probes are shown in Figures 5.8 and 5.9.

After assembly of the first batch of ten measuring probes, despite the modulator circuitry having been rigidly potted, it was found necessary to encapsulate the modulator connecting wires in a similar manner to the modulator in order to guarantee a complete absence of vibration-induced frequency modulation of the oscillator signal. Initially, the use of a silastomer potting material was investigated which, due to the ease with which it could be removed, would enable measuring

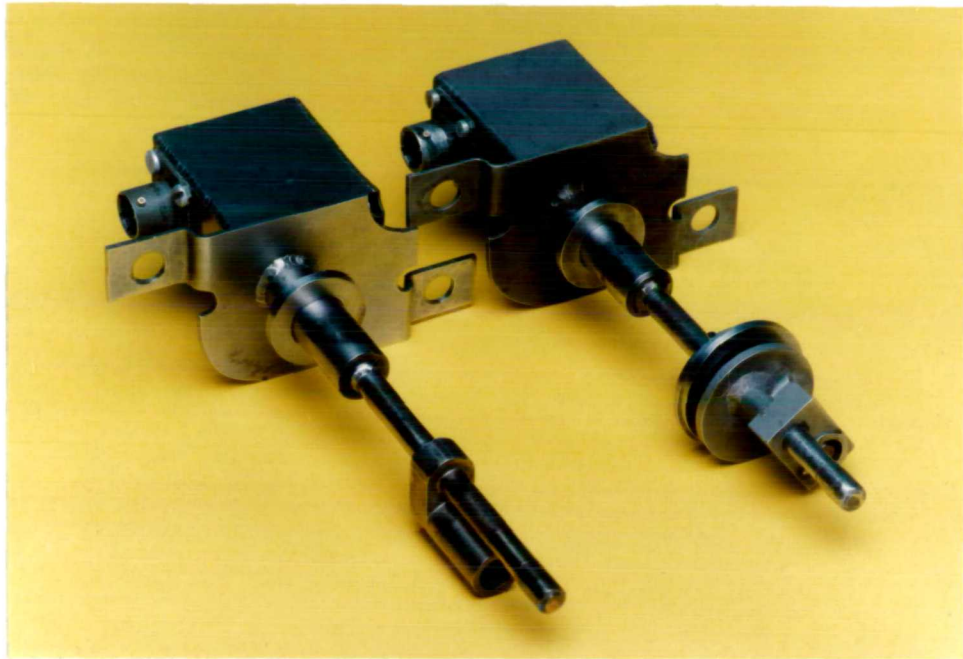


Figure 5.8 Photograph 1 of Assembled Measuring Probe.

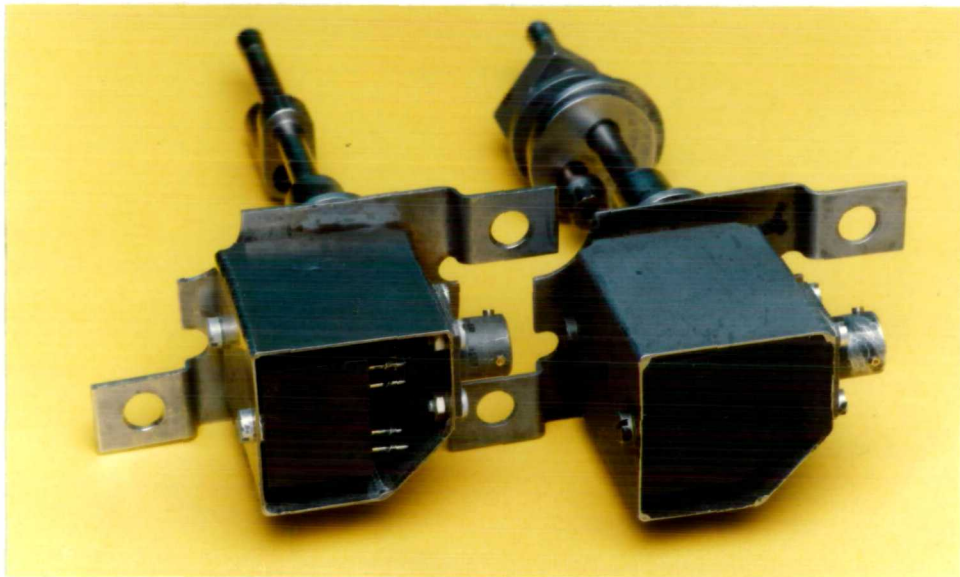


Figure 5.9 Photograph 2 of Assembled Measuring Probe.

probes to be repaired economically. However, even the small compliance of the silastomer relative to that of the filled epoxy resin was found to be sufficient to generate microphony.

Tests were then performed on the first batch of assembled measuring probes to quantify the effect on the measurement of tip clearance of changes of temperature of the probe electrode and the modulator.

First the probe electrode was heated by means of a hot air blower to a temperature of approximately 920K whilst measuring a series of known clearances between the electrode and the model spinning rig blades (previously described in Chapter 4.4.0.). The heating of the electrode assembly had no measurable effect on the measurement of clearance.

However heating of the modulator circuitry up to a maximum temperature of 370K degrees by the same means produced an average reading error of -8% in measured full scale clearance when the automatic frequency control circuitry was not activated. Selection of the automatic frequency control succeeded in restoring and stabilising the centre frequency of the oscillator and reduced the measurement error to an average value of less than -1.5% of full scale.

5.2.0 Groundstation.

The prototype groundstation is made up of ten discrete demodulator units and three power supplies to energise both the modulators and demodulators. Each demodulator module comprises a phase-locked loop circuit which demodulates the 10

MHz. carrier signal which is frequency modulated by the blade tip clearance information. Additional circuitry is included to derive an error voltage which is a function of the difference in carrier center frequency from a datum value. This error voltage controls the voltage regulator in the modulator such that the free-space oscillator frequency (ie the frequency when the measuring probe is remote from any earthed target), is maintained at the value set at the time of calibration regardless of the operating temperature of the measuring probe.

The developed circuit diagram is shown in Figure 4.21 and the printed circuit board layout is shown in Figure 5.10. Figure 5.11 is a photograph of a prototype demodulator module. Figure 5.12 shows a later Mark 2 demodulator, the modifications being intended to solve difficulties experienced during operation of multi-channel systems.

The major difference between the original and the Mark 2 demodulator, as proposed by a colleague, D.R.Foulds, consists of the addition of an r.m.s. converter circuit to the printed circuit board, thus avoiding the need for multiple discrete r.m.s. voltmeters. As discussed in Chapter 4.0, the r.m.s. voltmeter was required to integrate the individual blade passing signals in order to derive a signal which was a function of mean blade tip clearance. The other major improvement to the demodulator consists of exchanging the variable capacitance trimmer used to set the phase-locked loop voltage-controlled oscillator frequency for a fixed capacitor and exchanging a fixed resistor in the timing circuit for a 10 turn potentiometer. The potentiometer is considerably easier to adjust and set a frequency accurately and the long term

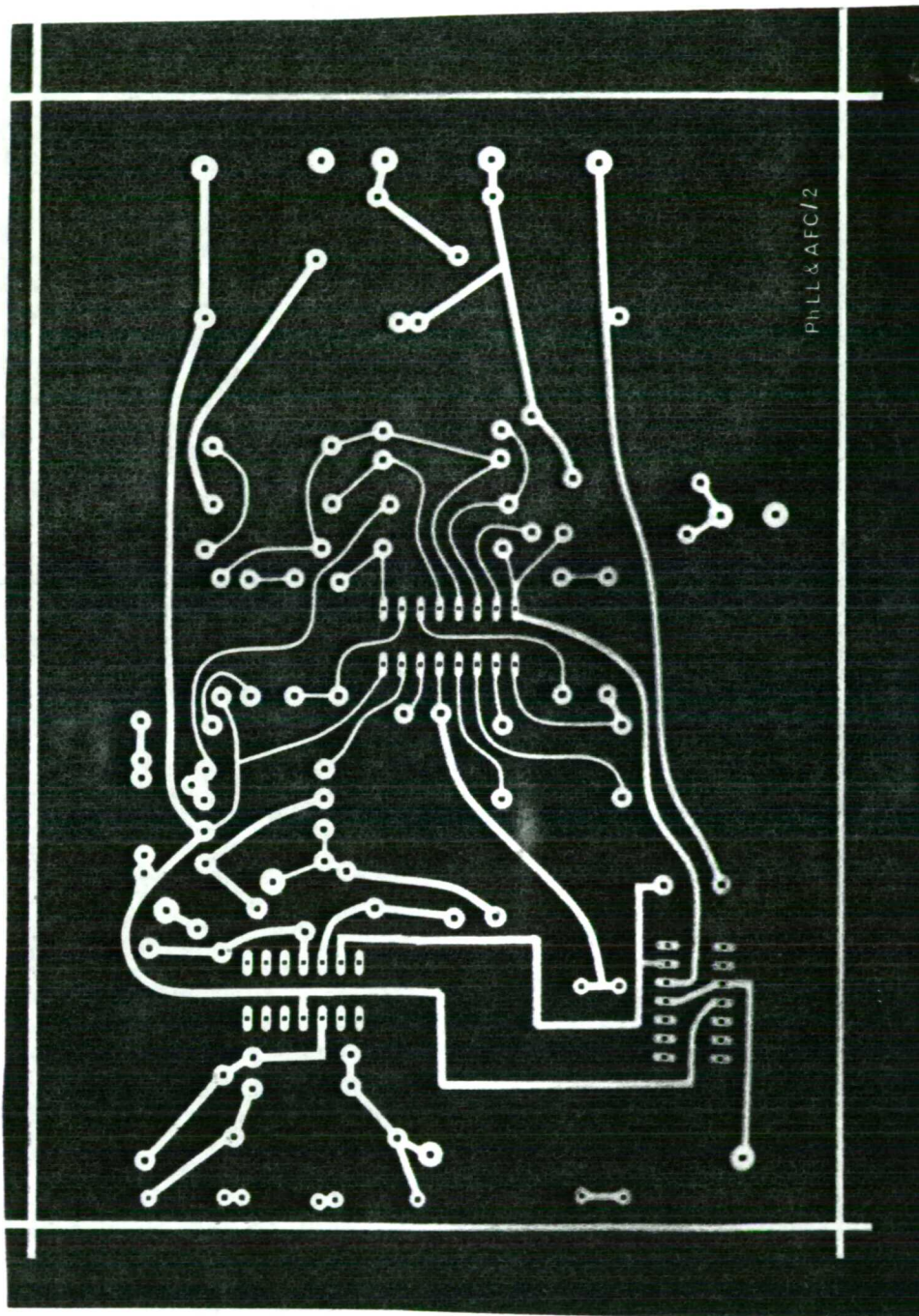


Figure 5.10 Demodulator/A.F.C. Amplifier Printed Circuit Design.



Figure 5.11 Photograph of Prototype Demodulator.

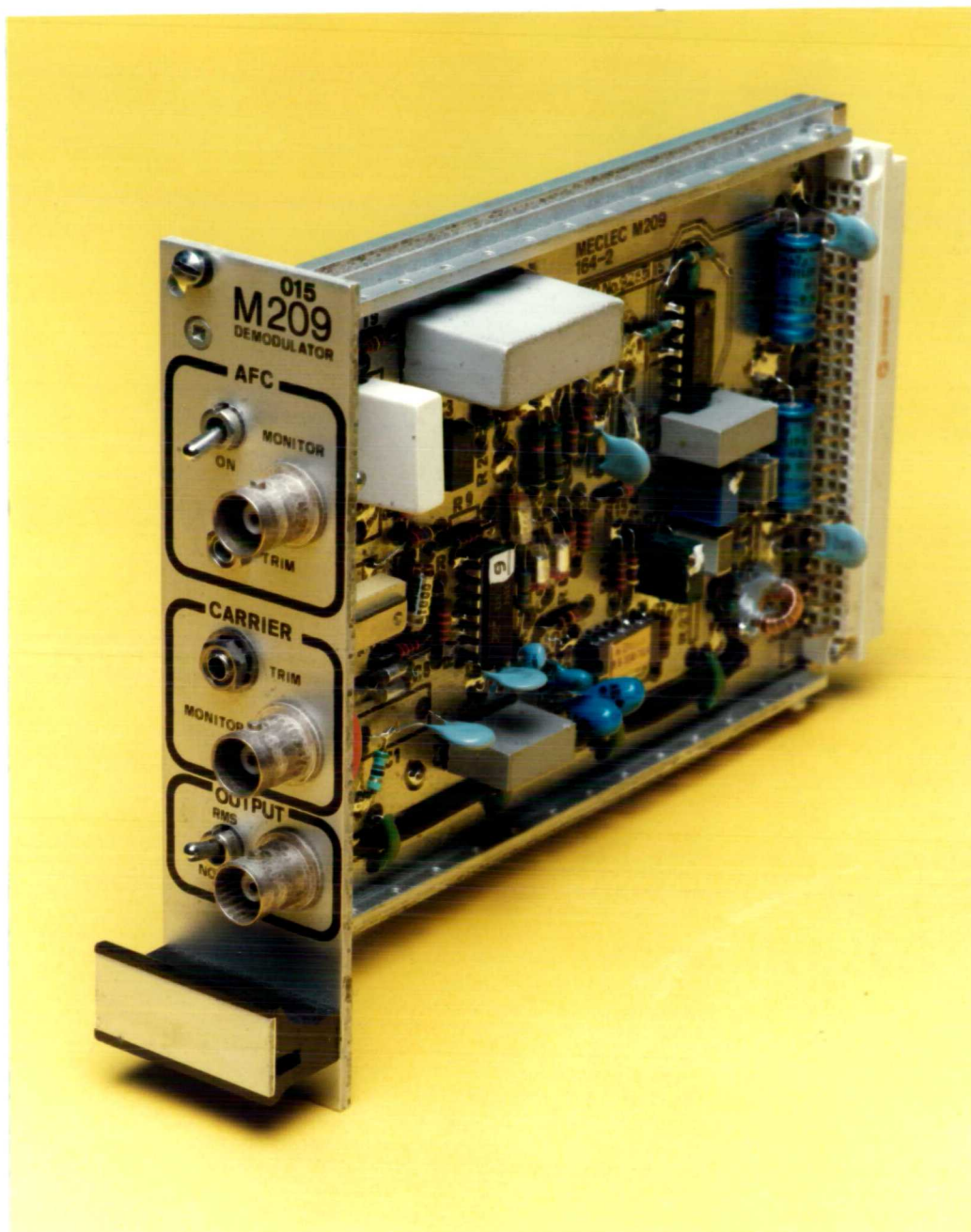


Figure 5.12 Photograph of Mark 2 Demodulator.

stability of the setting is also improved.

5.3.0 System Interconnection Standards.

In Figure 4.1, the f.m. capacitance clearance system components are shown schematically. In use the measuring probes would typically be mounted on the test vehicle- an engine or a component test rig- located in an engine test cell or an experimental test facility. The ground station would usually be located in or adjacent to the test control room (in a measurement facility), where adjustments could easily be performed during the operation of the test vehicle.

Consideration of the geography of the tip clearance measuring system components in a practical situation enabled an estimate to be made of the maximum length of cable required to connect the measuring probes to the demodulators contained within the ground station. The maximum separation was estimated to be 100 meters. During the design phase of the measuring probe modulator circuit, the need to transmit the oscillator signal over a considerable distance was anticipated. An amplifier was thus incorporated to drive a 50 ohm transmission line, this being the characteristic impedance of the most commonly available radio frequency coaxial cable.

During the initial testing of the first prototype system, continuous cable lengths of 100 meters or even greater, did not adversely affect the operation of the clearance measuring system. However operation of up to ten system channels simultaneously in the laboratory resulted in severe

interference between channels. This was discovered to be caused by crosstalk of the 10 MHz. carrier signals generating beat frequencies which fell within the passband of the demodulators. The level of interference affecting any one channel could be altered by changing the physical position of the particular measuring probe relative to any other operating measuring probe or by repositioning the interconnecting cables. Changing the frequency of oscillation of a measuring probe by adjusting the afc error voltage could affect both the amplitude and frequency of the interfering signal to adjacent system channels.

The system was then analysed in detail in order to identify the areas in which the potential for cross-channel interference to occur was greatest. These areas were then investigated systematically in the laboratory to first assess the contribution to the total interference of the area being examined, and second, to design and implement modifications to reduce or eliminate the crosstalk occurring within the area. It was determined at an early stage of the investigation that the interference was not being generated in just one area; a combination of sources were identified as follows:-

5.3.1 The Modulator/Demodulator Interconnecting Cables.

The interconnecting cables between the measuring probes and the demodulators consisted originally of 4 core individually screened P.T.F.E. insulated cable. Each screened conductor had a characteristic impedance of approximately 35 ohms. The four screened conductors were used to carry the +20 volts power

supply to the modulator module from the ground station, the system 0 volts line, the a.f.c. voltage and the 10 MHz. oscillator output signal at an amplitude of about 5 volts peak to peak. Measurements conducted at the end of a terminated cable without a measuring probe attached, indicated significant levels of induced carrier signals from other operating channels. This was found to be due to the poor quality of the cable when used as an r.f transmission line despite a specification which indicated its suitability for this application. The presence of 10 MHz. standing waves along the lines provided a classical mechanism for power transfer (crosstalk) between the cables.

The solution consisted of removing the oscillator signal from the multicore cable and transmitting this signal along a separate good quality 50 ohm r.f. coaxial cable. This had the effect of reducing the overall level of interference by approximately an order of magnitude.

It was appreciated during this work that in a practical installation it was extremely unlikely that continuous cable lengths could be used. Permanent facility mounted cables would be required with link cables being necessary at each end to connect to the measuring probes and the ground station. This configuration was simulated in the laboratory with three lengths of cable for each channel being joined together by means of in-line connectors. In order to keep the system crosstalk at the low levels achieved when using single lengths of cable, as opposed to the more practical situation of three lengths of cable per channel, it was found to be essential that the cable screens should be taken through the connectors on pins and not be earthed to the connector shells. The

recommended standard of wiring is shown for one channel in Figure 5.13.

5.3.2 Groundstation Rack Wiring.

Examination of the wiring within the groundstation rack unit for 10 MHz. carrier signals indicated significant levels present on the 20 volts power bus, on the 0 volt line and the a.f.c. control voltage lines. Decoupling of the power supply and a.f.c. lines by means of 10 nF disc ceramic capacitors directly to chassis earth and rewiring the 0 volt line in 14 s.w.g. tinned copper wire (as opposed to the thin hook-up wire used previously), significantly reduced the levels of crosstalk. This improvement (by a factor of between 2 and 3), together with the improvements described in the previous section (5.3.1), reduced the interference levels to negligible proportions, equivalent to a clearance in excess of 4 millimeters.

5.4.0 Data Processing and Display.

The output of each demodulator unit in the ground station is an analogue voltage in the range 0 to +4 volts which is the inverse function of the mean blade tip clearance sensed by each measuring probe. During the evaluation of the capacitance blade tip clearance measuring system on the Derby Development and Experimental Test Site, the analogue output signals from

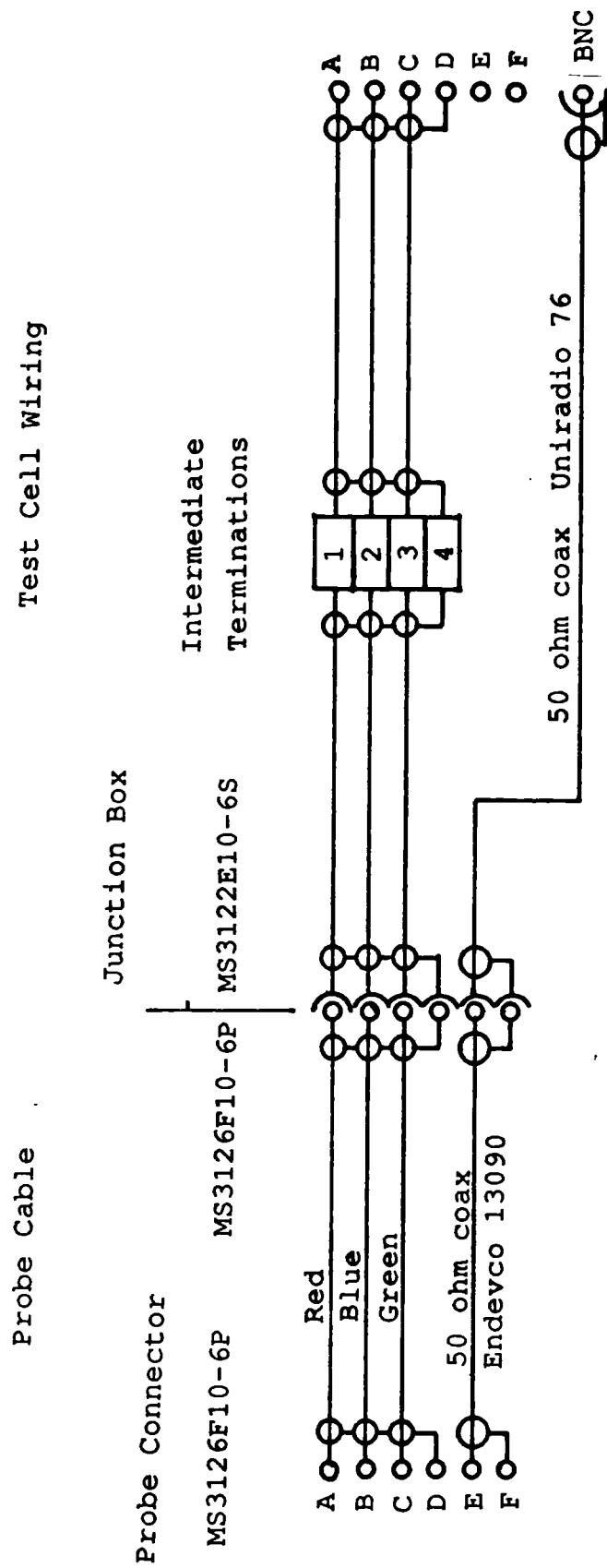


Figure 5.13 Measuring Probe/Demodulator Wiring Scheme.

the system were processed, displayed and recorded using an existing data acquisition facility known as the Transient Automatic Data Recording (A.D.R.) System.

The Transient A.D.R. system is configured schematically as in Figure 5.14 and is based upon a Modcomp 7840 Central Processing Unit. The system can process up to 64 analogue channels of data at scan rates of 100 scans per second down to 1 scan every 30 seconds. Data is logged on the local system disc as it is acquired and real-time plotting of up to 6 parameters in engineering units is possible using a Tektronix graphical display terminal. The Tektronix terminal is used to control the total data acquisition operation. To summarise, the following computing processes are carried out on the measured data:-

- * Digital filtering.
- * Conversion to engineering units (corrected where applicable).
- * Real time digital and graphical presentation.
- * Storage on local disc.
- * Simple calculations.
- * Post acquisition digital and graphical presentation.
- * Editing.
- * Transfer of selected data to the mainframe.

5.5.0 System Error Analysis.

The temperature coefficients of the components of the tip clearance measuring system were quantified by locally heating

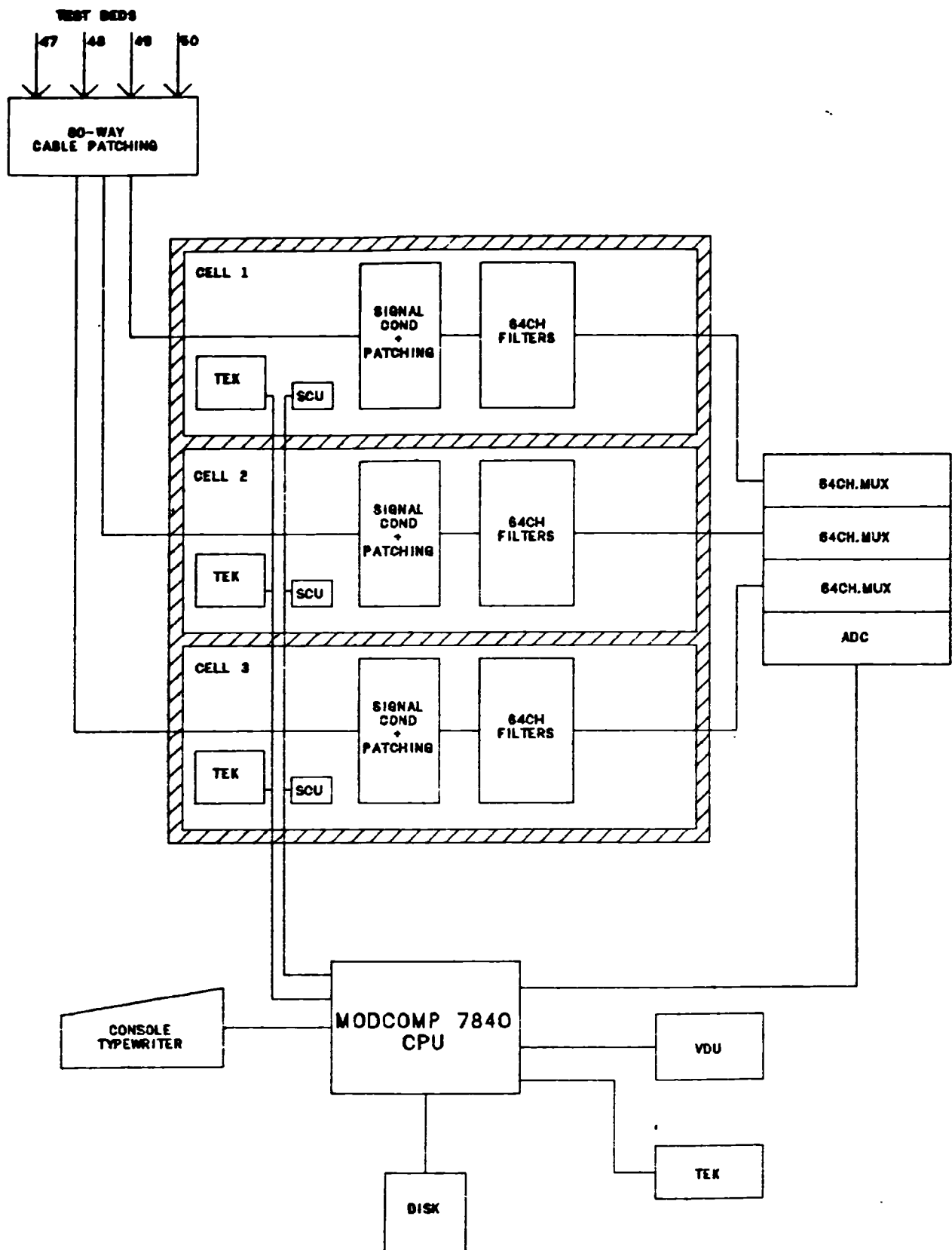


Figure 5.14 Schematic Diagram of Transient A.D.R. System.

each component in turn and measuring the effect on the the indicated clearance.

5.5.1 Measuring Probe - Sensor/Modulator

Temperature coefficient of measuring
probe-sensor (290 to 920K).....= < 0.1% f.s.
Temperature coefficient of measuring
probe-modulator (290 to 370K).....= -1.5% f.s.
Non-repeatability.....= < 0.1% f.s.

5.5.2 Demodulator/A.F.C.Amplifier/R.M.S. Convertor

Temperature coefficient of groundstation circuits
(290 to 320K).....= 0.3% f.s
Residual demodulator noise.....= 0.15% f.s
Non-repeatability.....= < 0.1% f.s.

5.5.3 System Calibration

Estimated setting clearance error.....= 0.1% f.s.

This analysis gives a root sum of squares system error of plus and minus 1.53 % of full scale (f.s.= 2.5mm), the figure being dominated by the comparatively large temperature coefficient of the modulator circuit. The clearance measurement error was observed to vary linearly with modulator temperature. Hence by restricting the temperature swing of the modulator when installed on a test vehicle by means of improved thermal insulation, increased cooling air supply etc., a significant improvement in system accuracy can be

obtained.

The target error band of plus and minus 5% of reading at a clearance of 1mm ie 2% f.s. can be seen to have been achieved.

6.0 CLEARANCE SYSTEM EVALUATION: ENGINE COMPRESSOR.

6.1.0 Introduction.

The first evaluation of the f.m. capacitance tip clearance measuring system in an engine environment was performed on a high pressure compressor, (HPC), of an Advanced Engineering engine. The investigation was initiated in order to fully understand a major service problem which had emerged with a civil gas turbine some two years after introduction into airline operation. A significant proportion of production engines were found to suffer a high speed surge between 30 and 60 seconds into take-off following an acceleration with a cold engine.

A surge of a gas turbine invariably results in a temporary loss of thrust and occasionally permanent damage is caused to air seals and blading which may reduce the engine efficiency. The phenomenon of surge occurs when a compressor is operated in an unstable regime and the air flow transiently reverses. The subject of surge was discussed in more detail in section 1.2.0.

The problem did not occur with a warm engine on take-off and the cold engine problem could be alleviated by a pre take-off warm up cycle. This procedure was however a temporary expedient since it resulted in queuing problems on runways and excessive fuel burn. A working party formed specifically to investigate the surge problem concluded that the loss of surge margin in the HP compressor during cold engine take-off could possibly be attributed to large transient tip clearances, HPC casing tilt and eccentricity and poor build standards in

service.

A new standard of HP Compressor casing was designed and implemented and succeeded in effecting a complete cure of the surge problem. The original problem, however, had not been fully understood, and hence the mechanism by which the cure had been achieved was uncertain. With this background, following the introduction of the new standard of HP Compressor casing, no changes could be permitted to the design for fear of re-introducing the original surge problem. An investigation which comprised two heavily instrumented engine tests, one with the original standard of HPC casing followed by one with the redesigned HPC casing, was subsequently proposed. These "back-to back" tests were regarded as essential in order to obtain an understanding of the mechanical behaviour of the compressor. This would allow future designs of HPC casing for the next generation of gas turbines to preserve an adequate surge margin under all normal engine operating conditions.

The engine tests required the measurement of rotor blade to casing clearances in addition to the measurement of the movement of other components and the measurement of metal and air temperatures. In total, some 95 transient measurements were specified for the HPC.

In this investigation the accurate and reliable measurement of blade tip clearance was regarded as crucial. The on-line direct measurement of blade tip clearance on an engine had never previously been attempted, hence two different measurement techniques were proposed. The first was a development of the Fenlow electromechanical system used for many years on compressor and turbine component test rigs,

known as the Stepper Motor Probe system (Ref.section 1.4.0 Survey of Previous Work). The second proposed measurement technique was the f.m capacitance system.

6.2.0 Test Objectives.

The objectives of the first engine test, which incorporated the old surge-prone standard of compressor casing, were as follows :-

1. Validate the blade tip clearance measurements produced by the Stepper Motor Probe system.
2. Validate the blade tip clearance measurements produced by the F.M.Capacitance Probe system.
3. If either or both the preceding measurement techniques proved to be successful, investigate the compressor tip clearances and the casing movements implied by the probes in conjunction with the other instrumentation for:-

- * Acceleration/Deceleration manoeuvres.
- * Hot re-slam (maximum acceleration from idle to take-off thrust rating.)
- * Casing distortions.
- * Effect of 'A' frames (the structures through which the thrust of the engine is transmitted to the aircraft.)
- * Effect of fan out of balance.

The objective of the second engine test with the improved

design of HPC casing was as in 3, the validity or otherwise of the tip clearance measuring techniques having been established in the first engine test.

Following the engine tests with the different standards of HPC casing, the mechanical behaviour of the two designs could be compared and contrasted. With the knowledge that the later design had effectively solved the surge problem, a code of practice could be written which would enable future casing designers to avoid the inadequacies of the original design.

6.3.0 Probe Installation.

The capacitance probes which were used for the HP Compressor tip clearance measurements were as shown in Figures 5.7, 5.8 and 5.9. The alternative electromechanical stepper motor probes were designed to be interchangeable with the capacitance probes in the compressor casing, a photograph of one is shown in Figure 6.1.

The engine compressor to be instrumented was a 6 stage axial flow design and initially the measurement requirement was to install clearance probes on the first and last stages of the compressor. However due to difficulties in physical access a compromise was reached in which four probes were fitted to stage 2 (D110A to D) and four probes fitted to stage 5 (D111A to D) of the compressor. The circumferential and axial locations of the probes are shown schematically in Figures 6.2 and 6.3 respectively. Figure 6.2, which is a longitudinal sectioned view of the early surge-prone HP compressor, also identifies the locations of some of the other instrumentation

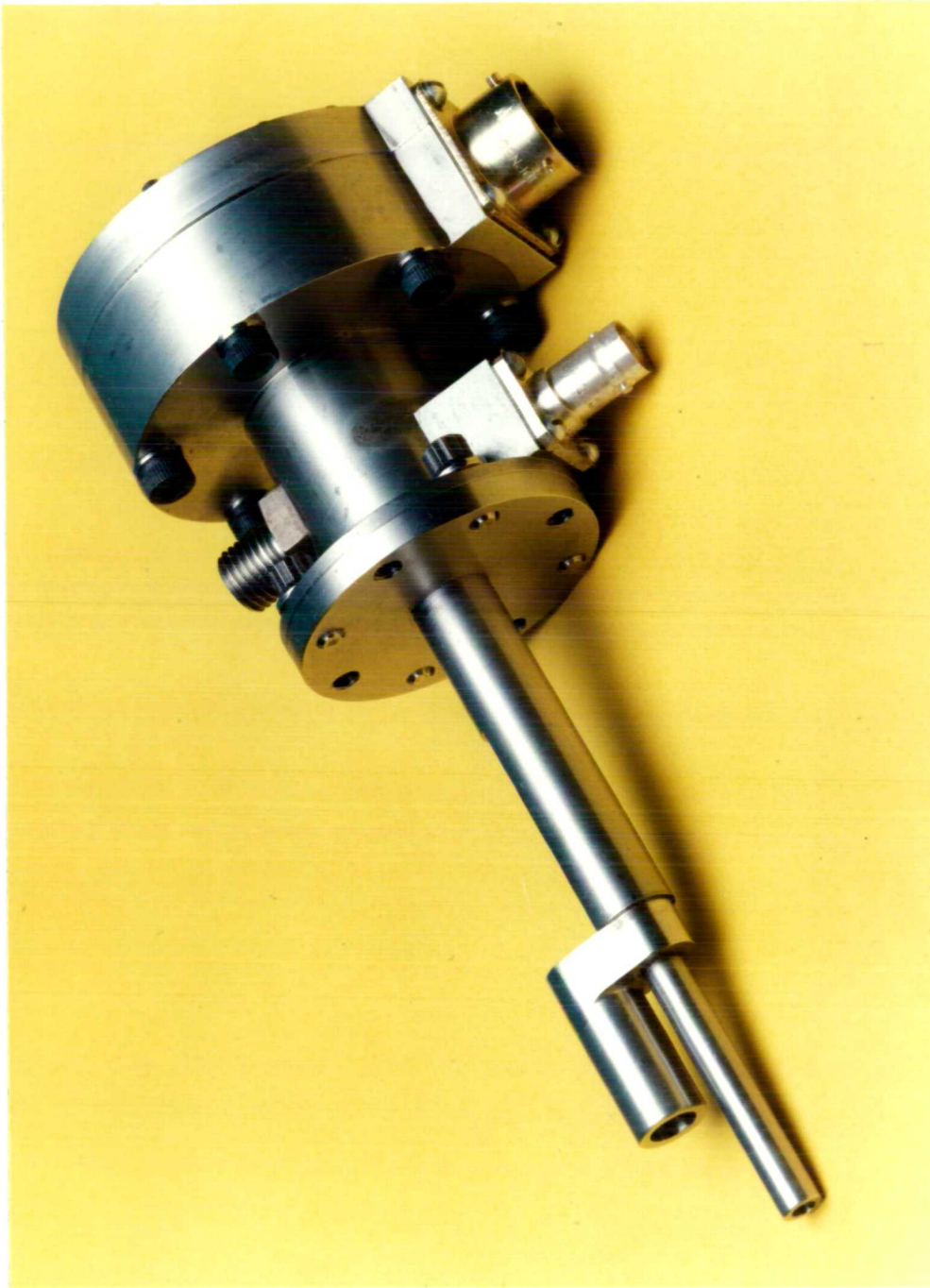


Figure 6.1 Electromechanical Stepper Motor Probe.

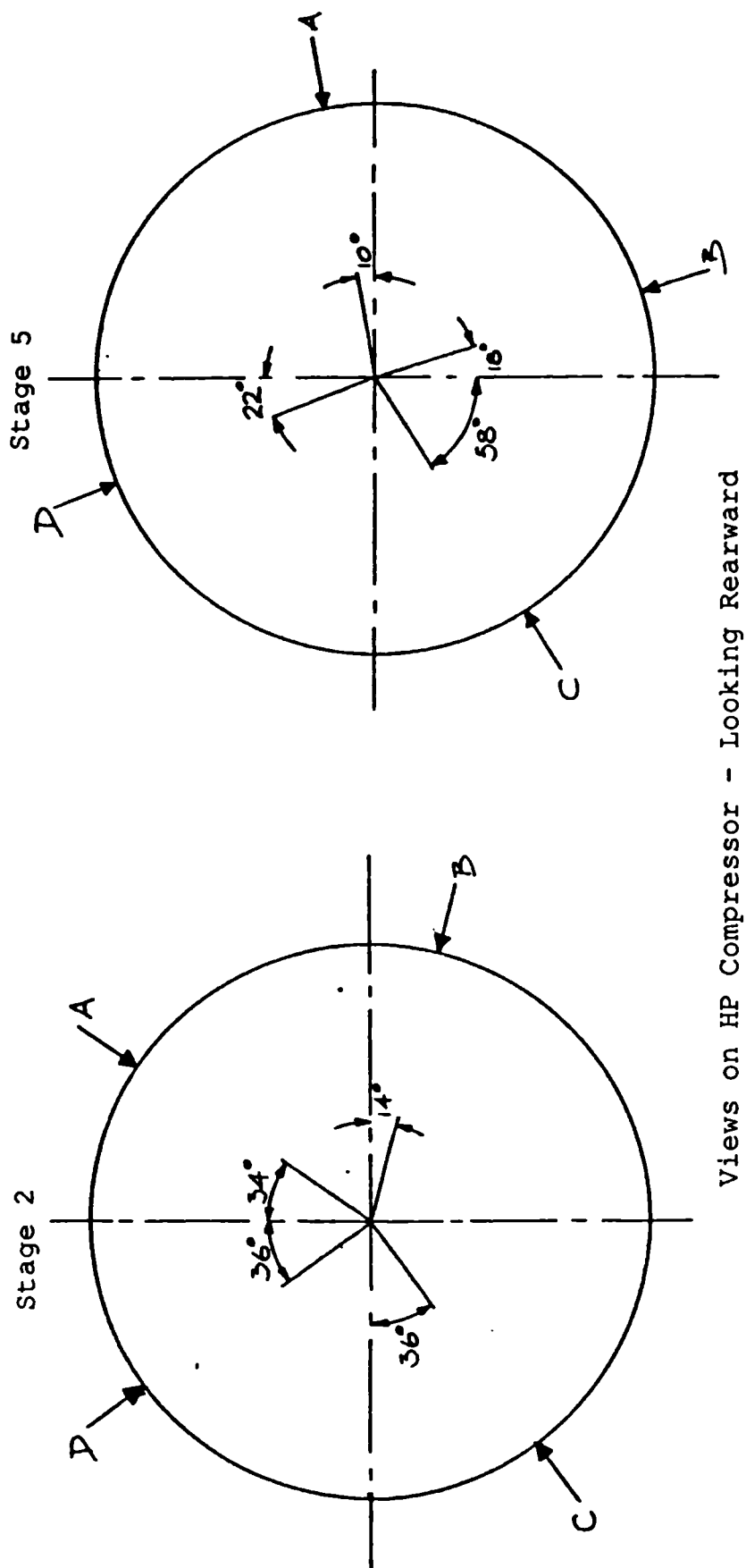


Figure 6.2 Circumferential Locations of Tip Clearance Measuring Probes.

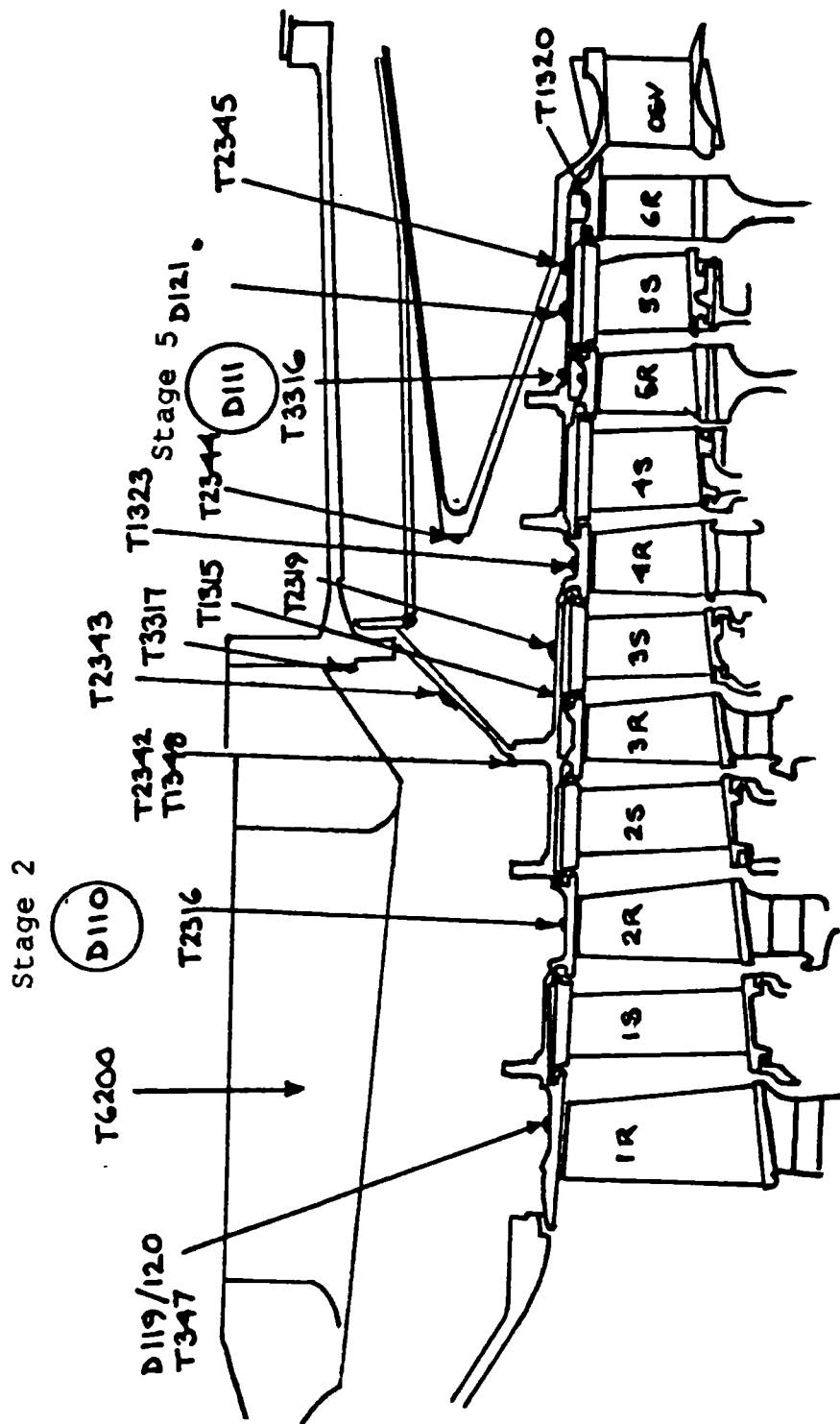


Figure 6.3 Axial locations of Tip Clearance Measuring Probes.

required in the experiment to measure metal temperatures, gas temperatures and displacements.

The f.m. capacitance probes as designed had a measuring range of 2.5mm. In order to obtain clearance measurements throughout the engine operating envelope, it was essential that the cold static build clearance for each probe was set such that :-

- * The blade tips were at all times within the operating range of the probes.

- * The minimum predicted probe to blade tip clearance should be no less than 0.5mm. This requirement generally resulted in the probes being mounted in the compressor casing with their sensing electrodes initially under-flush of the abradable material used to line the casing over the rotor path.

The cold static build clearance of each probe, however, could not be measured directly once the compressor was fully assembled and the capacitance probes fitted to the casing. A series of drop-check measurements from nominated datum faces on the compressor casing to the blade tips of rotors 2 and 5 and to the probe mounting faces were made. From these measurements the absolute separation between the sensing electrode of each probe and the rotor blades passing underneath could be calculated. Figure 6.4 shows the measurements which were made. Dimensions G1 to G4 and H1 to H4 were obtained prior to the compressor being assembled. Dimensions E1 to E4, J1 to J4, K1 to K4 and F1 to F4 were measured using a drop-micrometer after the compressor had been fully assembled. From these measurements the build clearances

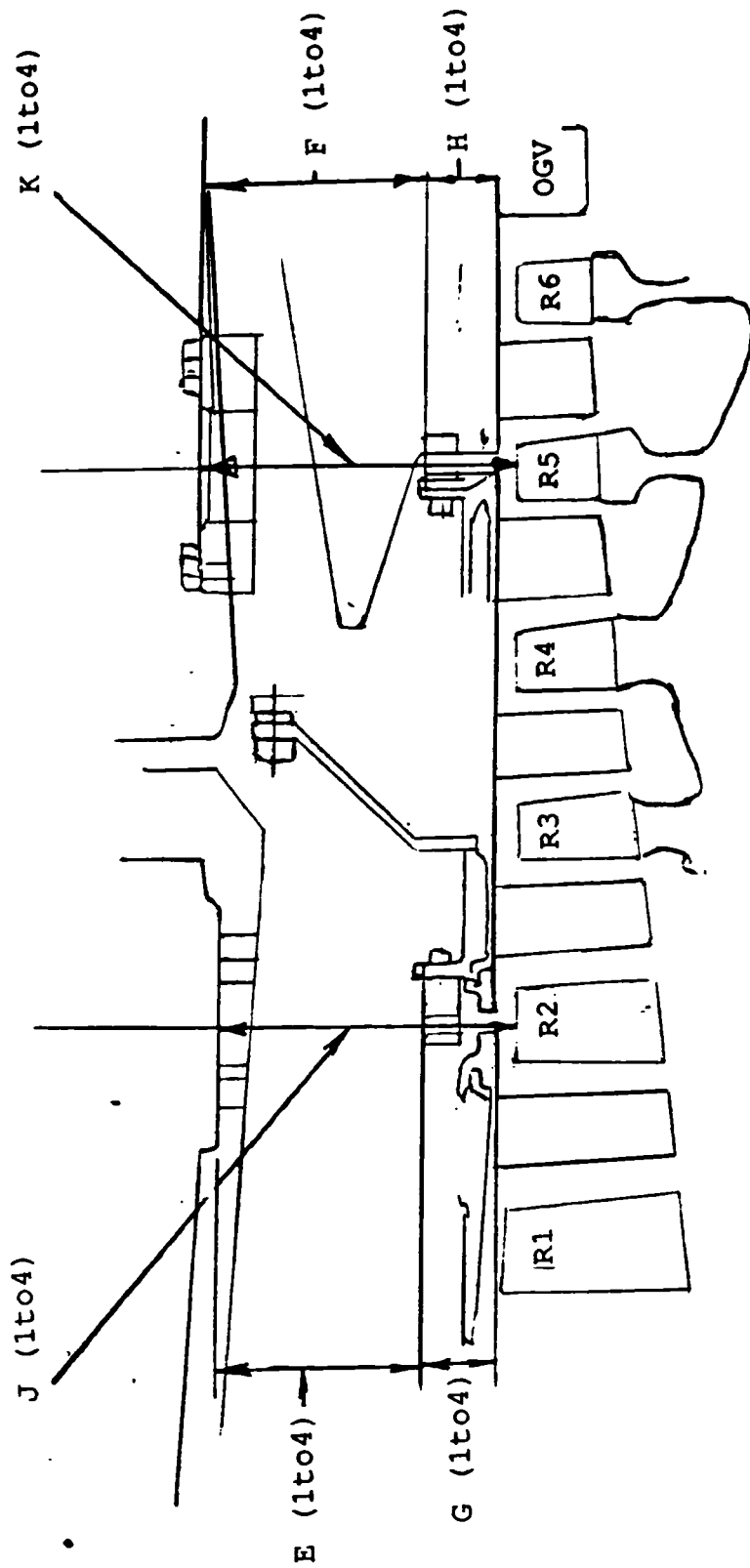


Figure 6.4 Compressor Probe Measurements.

were calculated using the following relationships:-

$$\text{Stage 2 Tip Clearance} = J - (E + G)$$

$$\text{Stage 5 Tip Clearance} = K - (F + H)$$

6.4.0 Capacitance Probe Calibration.

6.4.1 Calibration Equipment.

As discussed earlier in section 4.4.0, the relationship between the absolute clearance and the f.m. capacitance clearance measuring system output is determined by :-

- * The geometry of the application i.e. the blade thickness, blade tip stagger angle, probe sensing electrode diameter and the mark/pitch ratio of the blades.
- * The measuring probe/demodulator combination.

Thus for the proposed engine tests during which the blade clearances were to be measured, each measuring probe was assigned to a demodulator module to form a measurement system channel. Each channel was then calibrated to establish its particular clearance/voltage characteristic using the actual rotor blades as targets. This was achieved by mounting the bladed HP compressor rotor, prior to its assembly into the compressor casing, in a framework referred to as a " tip cropping fixture ". The fixture was designed to locate compressor rotors in bearings whilst the tips of all the blades in a stage were machine ground to a uniform design

diameter. For the purposes of calibrating the capacitance probes the fixture was simply used as a convenient means to spin the rotor whilst varying the distance between the probes and the blade tips.

The fixture with the HPC rotor installed is shown in Figure 6.5. A capacitance measuring probe is shown clamped to a machine slide which is capable of resolving linear movements in a radial direction to the rotor axis to 0.025mm. The associated electronic equipment required for calibration is also shown in the photograph and includes the rack of demodulator modules, carrier frequency counter, rms voltmeter and oscilloscope.

6.4.2 Calibration Procedure.

The probe to be calibrated is first mounted on the machine slide which is then positioned over the relevant blade stage, stage 5 in Figure 6.5. The probe is then connected to the assigned demodulator module and with the AFC selected off, the AFC trim is adjusted to give 2.00 volts plus or minus 0.02 volts measured at the AFC MON socket with a digital voltmeter. With the AFC now selected on, the VCO TRIM is adjusted to give the same reading as before, ie 2.00 volts. The carrier frequency is noted and should lie between 9.5 and 11 MHz. with an amplitude of greater than 250mV peak to peak. The demodulator output should be steady and have less than 8mV rms of random noise. The rotor in the fixture is then rotated at a speed of at least half to one revolution per second by means of a small electric motor.

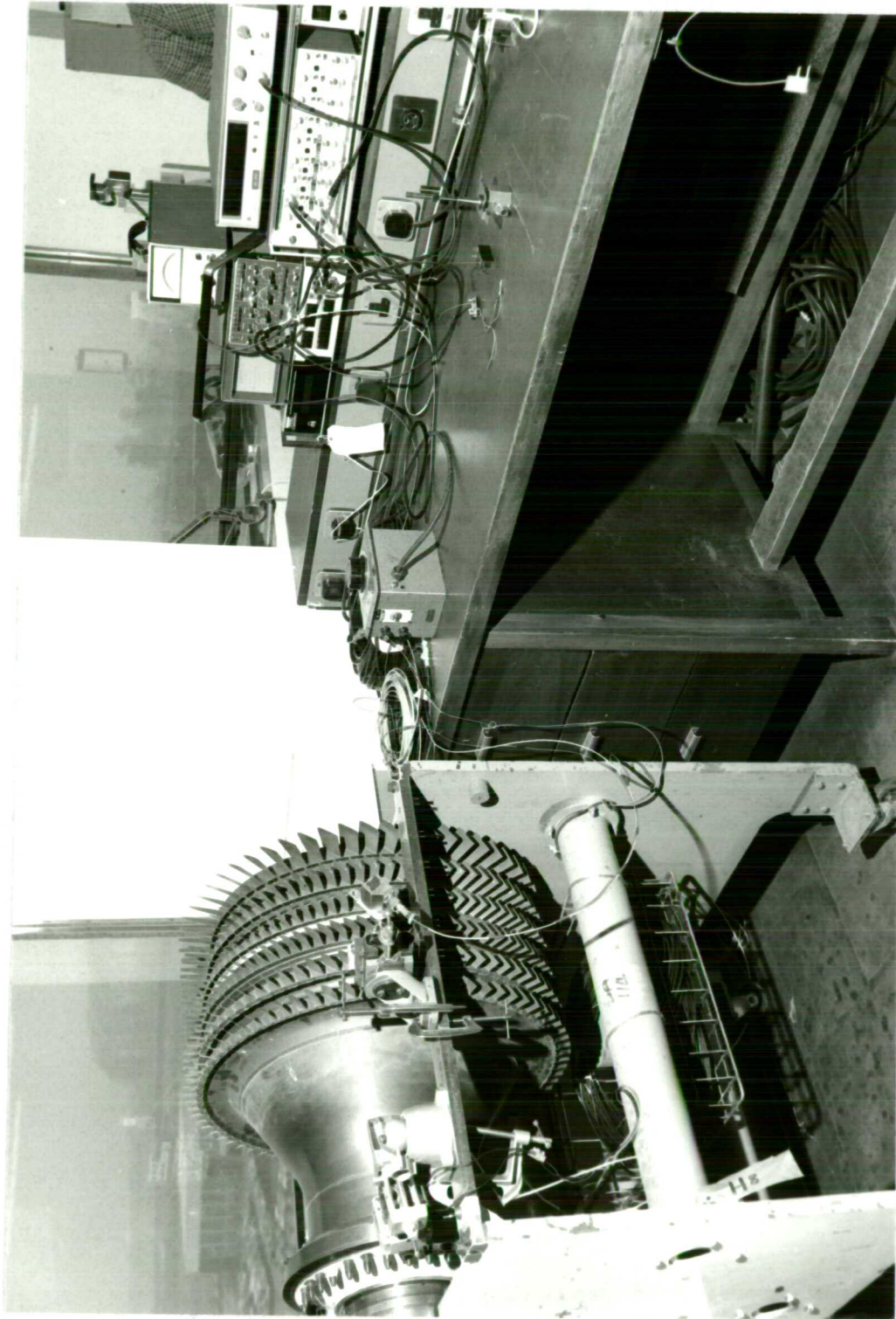


Figure 6.5 HP Compressor Rotor in Tip Cropping Fixture.

The probe, which is now looking radially into the rotor over the relevant stage, is now advanced towards the rotor by means of the machine slide until the blades which are longest gently brush the end of the probe. The reading on the micrometer at this point is the zero clearance value and the absolute accuracy of the probe calibration depends upon how accurately this initial zero datum condition is set.

The probe is now retracted by at least 1 mm. and then advanced to give a clearance of 0.05mm. The output of the demodulator, as measured either by the external rms voltmeter or by the internal rms voltmeter of the later mark 2 demodulators, is noted along with the carrier center frequency. Winding the probe well away from the blades before moving in to the next clearance point ensures that there are no errors in the calibration due to backlash in the micrometer screw. The procedure is repeated in 0.05mm clearance increments up to 0.25mm, 0.1mm increments up to 1mm and 0.25mm increments up to 3mm.

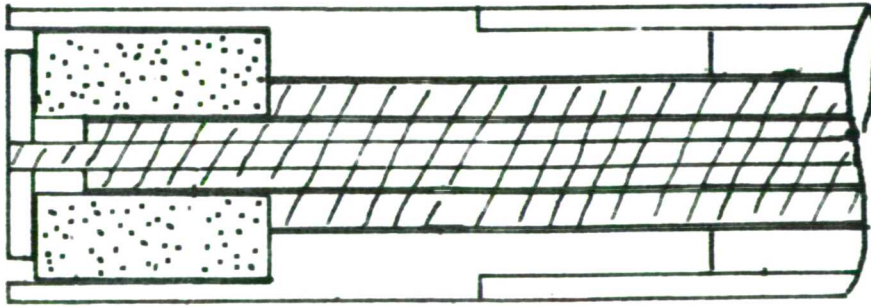
During the probe calibration the clearance versus voltage output is plotted to validate the calibration and to enable any suspect points to be investigated during the calibration. This procedure was repeated seven more times so that four probes were each calibrated for rotor stages 2 and 5. Channel to channel sensitivity variation was found to be in the order of plus and minus 25% of average sensitivity.

6.4.3 Probe Immersion Sensitivity.

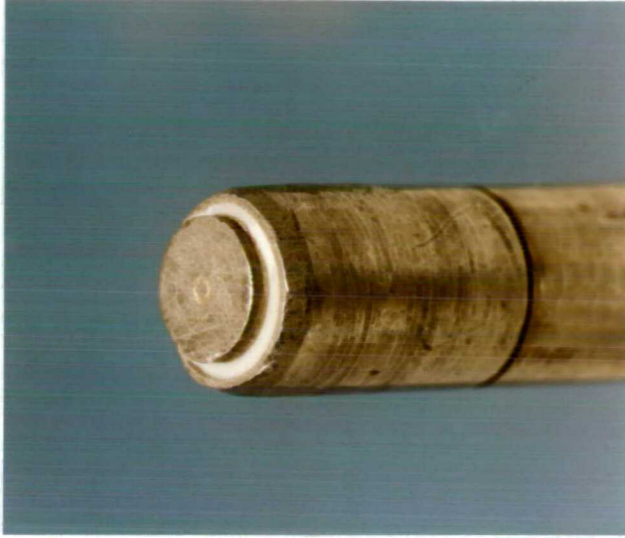
Following the calibration of the capacitance probes on the tip cropping fixture, the probes were trial fitted to the engine compressor and connected up to the demodulators and voltmeters. In order to check the build clearances, the rotor was turned slowly by hand to generate a reading from the probes. Without exception, the clearances as indicated by the probes were too large. For an expected build clearance of 1.50mm, the capacitance probes typically indicated a clearance some 0.18mm greater, ie the system voltage output was consistently lower than expected. The probe calibrations on the tip cropping fixture were checked and found to agree with the original calibrations to better than 0.025mm, which was estimated to be well within the experimental error.

At this stage the geometry of the probe/installation was audited in detail in order to find an explanation for the discrepancy between measurements made on the calibration fixture and those obtained on the engine.

The geometry of the measuring probe sensor was essentially as shown in Figure 6.6 a). However, close inspection of the probe tips as manufactured revealed a difference in detail. The outer housings of the probes, which were designed to be flush with the sensing electrode surface, had, at some stage during manufacture, been machined back so that they were now level with the surface of the alumina insulating bush, as shown in Figure 6.6 b). The reason for this modification to the probe geometry was discovered to be to facilitate the removal of the excess conductive braze material after heating the assembly in



a) As Designed.



b) As Manufactured.

Figure 6.6 Capacitance Measuring Probe Sensor

the vacuum brazing furnace. The significance of machining back the earthed housing such that the electrode now appeared proud of the assembly was not fully appreciated during manufacture and had not been detected during final assembly and calibration.

The installation of the modified probe tip in the compressor casing is shown schematically in Figure 6.7. It can readily be seen that the close proximity of the electrically earthed compressor casing effectively generates a small but significant shunt capacitance in parallel with the measured capacitance to the rotor blade tips. The result is a desensitising of a measuring probe when installed in the compressor casing in comparison with the sensitivity of the probe when installed in the tip-cropping fixture, where the probe tip is located in free space.

Due to the imminence of the engine test, it was not considered practical or feasible to modify the manufactured probes back to the original design. A compromise solution was adopted in which the probes were re-calibrated in the tip-cropping fixture whilst mounted in a short section of compressor casing, thus fully simulating the engine installation geometry during the calibration. A photograph of a typical probe mounted in a section of compressor casing prior to calibration is shown in Figure 6.8. Figure 6.9 shows the probe/casing assembly attached to the tip-cropping fixture whilst calibrating the probe for a stage 5 position.

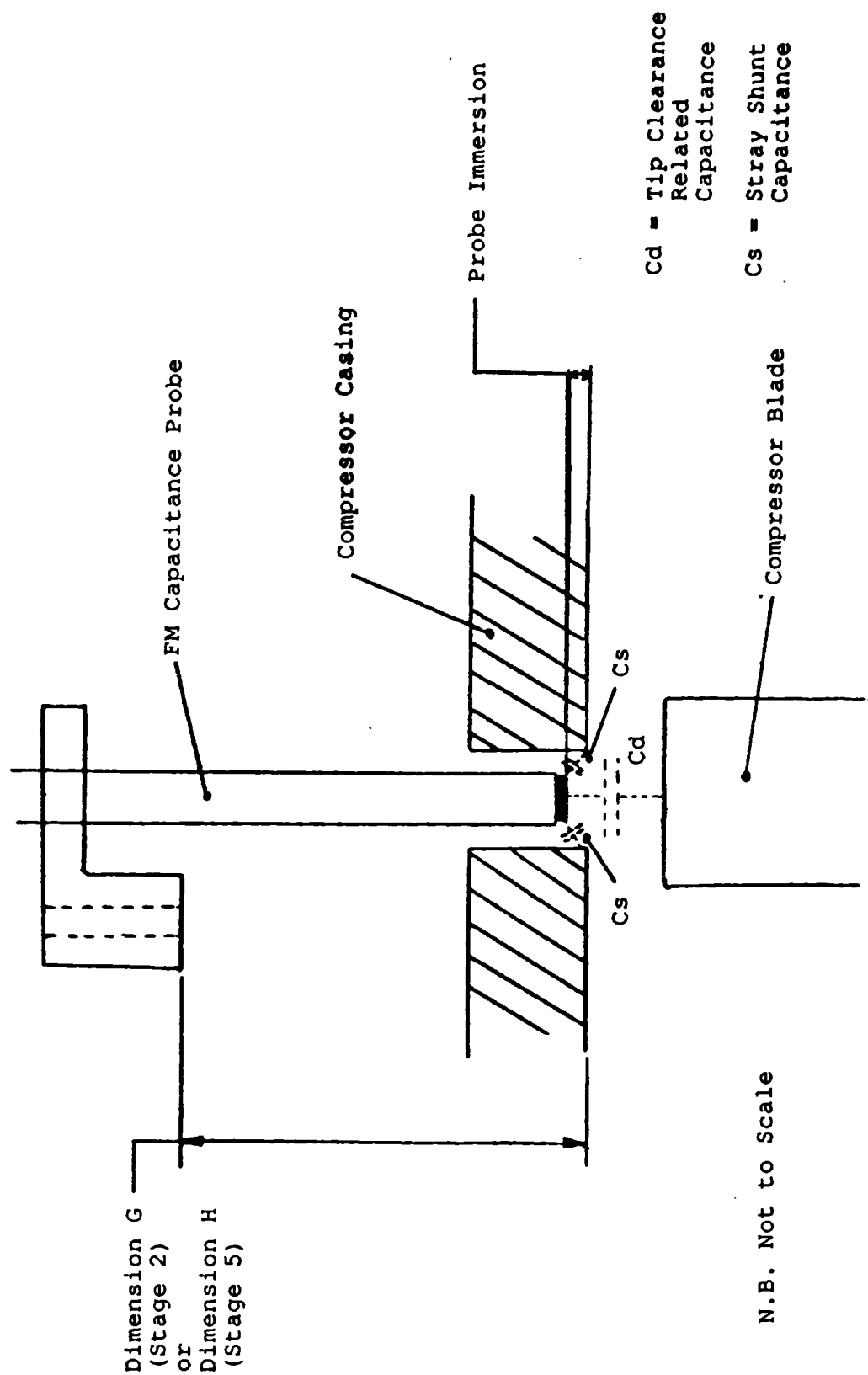


Figure 6.7 Schematic Diagram of Installed Modified Probe Sensor.

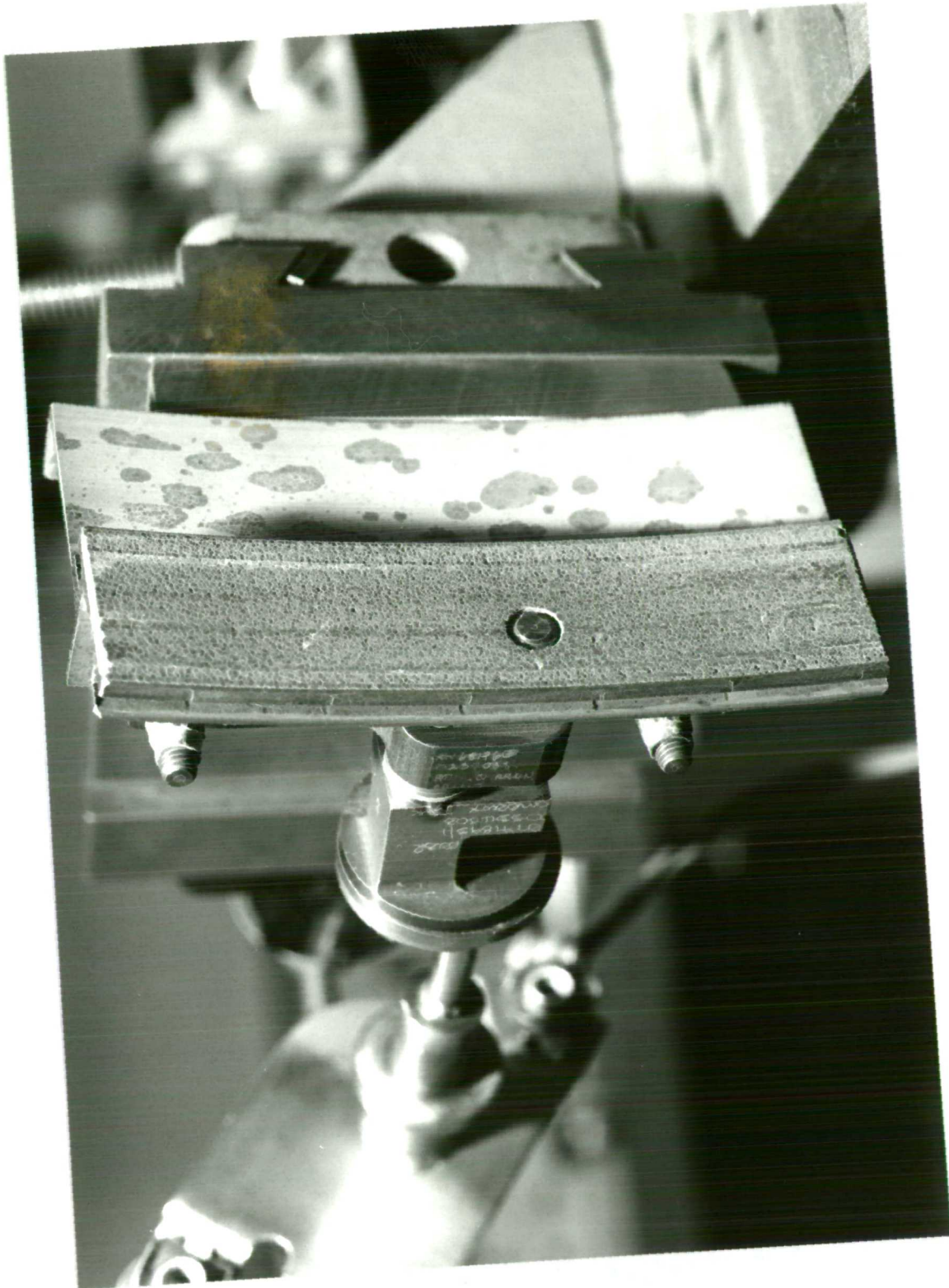


Figure 6.8 Measuring Probe Mounted in Section of Compressor Casing.

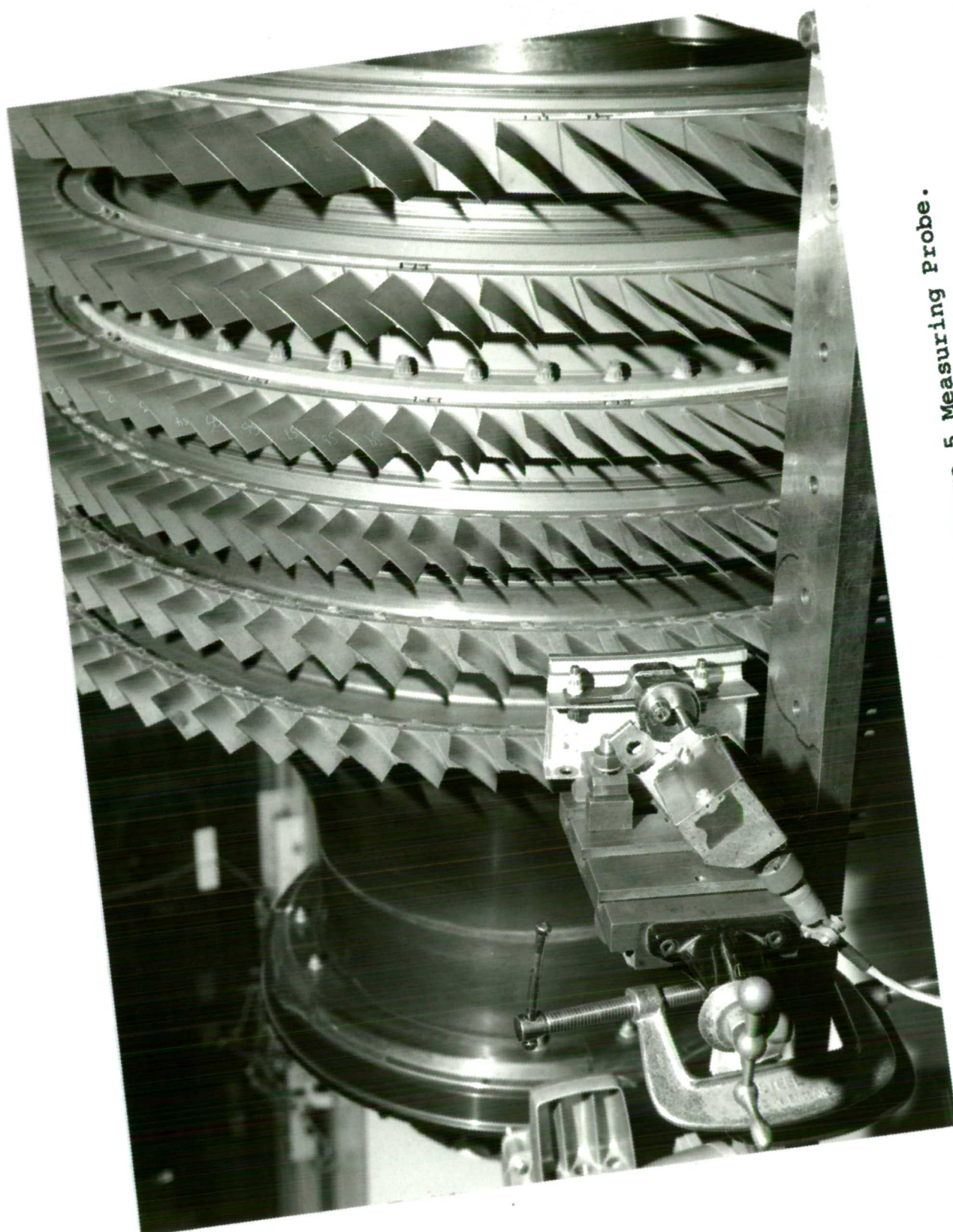


Figure 6.9 Calibration of Stage 5 Measuring Probe.

6.4.4 Installed Probe Calibration Validation.

Having become aware of the immersion sensitivity of the measuring probes, all probes were re-calibrated for three immersions in the compressor casing; 0.5mm, 0.75mm and 1.00mm underflush of the lining material. Subsequently, when using the calibration appropriate to the particular channel of probe/demodulator and immersion of the probe, the clearances as measured by the capacitance probes agreed very closely (within 0.03mm) with the physical measurements. A further check was carried out on the engine installation whereby a washer of known thickness was inserted underneath the mounting face of each probe in turn to move the probe radially outwards by a known amount. Measurements were then obtained from the probes by turning the engine rotor by hand. Taking into account the small change in calibration which occurs due to the change in probe immersion, each probe should in effect increase its measured clearance by the thickness of the washer. This they did without exception to within 0.03mm, which was considered to be a satisfactory validation of the probe calibration procedure and the use of this calibration for the engine installation.

6.5.0 Engine Test Programme.

6.5.1 Surge-Prone Compressor.

Initially, when the engine was delivered to the sea level test bed at Derby, the electromechanical stepper motor probes were

fitted to the engine compressor to measure the transient radial tip clearances on stages 2 and 5. In spite of a high level of care and attention to detail during the manufacture, assembly and calibration of the eight stepper motor probes, the mechanical reliability when installed in the engine was such that the complete test programme was jeopardised. The decision was taken to abandon the SMP testing and rely exclusively on the fm capacitance probes.

After installation of the engine on the test bed, the tip clearance probes were connected to the demodulators located in a measurement facility via the long interconnecting cables. The remainder of the engine instrumentation was connected to the test bed mounted data acquisition system.

When the capacitance tip clearance system was first switched on, intolerable levels of interference were present on most of the channels. The interference was found to consist of beat frequencies within the passband of the demodulators generated by the mixing of the various carrier frequencies, nominally 10 MHz., a problem which had been identified earlier in the laboratory (section 5.3.0).

The solution to the interference problem lay in correcting the wiring between each probe and its demodulator so that it conformed to the standard shown schematically in Figure 5.13. In particular, the isolation of the screen of the rf coaxial cable, which transmit the carrier signal, from various engine and test cell earths was found to be particularly effective.

Once the instrumentation was confirmed operational, the engine was dry cranked (rotated using the air starter with no fuel

supplied to the engine) for two minutes, reaching approximately 25% speed (2500 rpm). The tip clearance readings obtained during the crank indicated clearly that two of the eight probes had not seated correctly in the casing, both measuring tip clearances in excess of 4mm as compared with build clearances of 1.25 to 1.50mm. Removal of these probes revealed that the probe tips had not fully passed through the compressor inner casing due to a small mis-alignment of the access holes, consequently suffering damage as the fixing bolts were tightened. Although the damage to the probe tips was considerable, the sensing electrodes in both cases were unharmed. The outer probe sleeves were dressed using a file, straightened and refitted successfully. A second dry crank indicated all probes were correctly located and operational. The clearances measured were noted and taken as the datum values against which all other measurements were compared.

The decision was made to carry on with the test schedule, the next step being to supply fuel to the engine, ignite it and reach a ground idle (GI) condition. This was achieved with no further problems, after which the engine was shut down and allowed to cool. During a subsequent dry crank the datum tip clearance readings were repeated.

The engine was then taken through an abbreviated version of a Production Pass-Off schedule consisting of rapid accelerations, decelerations and hot reslams. Throughout this testing the probes appeared to give credible results.

The next item on the test schedule consisted of operating the engine through a number of simulated flight cycles. These

consisted of setting the engine sequentially at thrust levels consistent with those used for take-off, climb, cruise, descent, approach, landing, reverse thrust and idle. During this testing the output from the probes in positions D111A, D111B and D110B started to deteriorate. An inspection of the probes indicated that one probe (D111A), had failed electrically , no carrier being present. This was replaced with a previously calibrated spare probe. The other two faulty probes were found to be undamaged, the problem eventually being traced to an interconnecting cable joint which had overheated due to a leak of high pressure, high temperature bleed air. After these cables had been replaced, the full set of eight probes were again fully operational.

The final test schedule items subjected the engine to a series of soak-back tests, hot re-slam accelerations and fuel spike tests. The intention of the fuel spike testing was to determine the surge margin of the compressor by progressively increasing the volume of fuel injected into the engine in a single shot. This had the effect of instantaneously raising the working line of the compressor until the spike was sufficiently large to destabilise the compressor and surge occurred. Although the design of compressor being tested reputedly had a low surge margin, surge could not be induced. Not until the fan was deliberately unbalanced was a full power triple surge provoked 20 seconds after a 12 second acceleration from GI to MTO. The probes all survived the shock of surge.

The final test item involved re-balancing the fan and replacing the standard "A" frame locating pins with pins having an increased diametral clearance of 0.5mm. Again the

probes functioned well.

The engine was de-rigged from the test bed with all probes fully operational after nearly 15 hours of engine running time.

6.5.2 Surge-Free Compressor.

The test schedule for the next build of the engine with the improved design of compressor casing installed was identical to that used for the earlier build. This time no problems were encountered with wiring-induced cross-talk interference. However, due to the use of a lower pressure probe cooling air supply, at MTO conditions the stage 5 probes in particular tended to overheat, temperatures of 358 to 363K being reached. The provision of an additional slave air supply cured the problem and ensured the probe temperatures never exceeded 333K. Apart from two probe cables needing replacement due to physical damage, no probe problems occurred at all. Prior to removal of the engine from the test bed, two probes, D111A and D111D, were interchanged to check that different probes in the same positions read the same.

6.6.0 Discussion of Results.

6.6.1 Tip Clearance Probe Analysis.

The tip clearance data generated by the two engine tests was intended for use in developing or modifying the existing theoretical model of the compressor structures. The consequences of using experimental data which was in error could potentially be very serious. Unfortunately no experimental tip clearance data was available from previous tests against which the capacitance probe results could be compared and validated. This exercise represented the first time that the continuous measurement of tip clearances on an engine compressor had been attempted. The validation of the experimental data was thus confined to comparison of the test results with predictions of tip clearance variations for simple manoeuvres which could be made with a high level of confidence.

Simple engine accelerations and decelerations between GI and MTO were examined for both compressor stages and the constituent growths, as indicated in Figure 6.10, were calculated. The assumption was made that if the experimentally obtained data was in close agreement with the theoretically derived data under these circumstances, the experimental data derived from manoeuvres which did not lend themselves to confident theoretical analysis would be accurate.

The engine measurements of rotor path temperature were used to evaluate approximate casing thermal growths from the expression :-

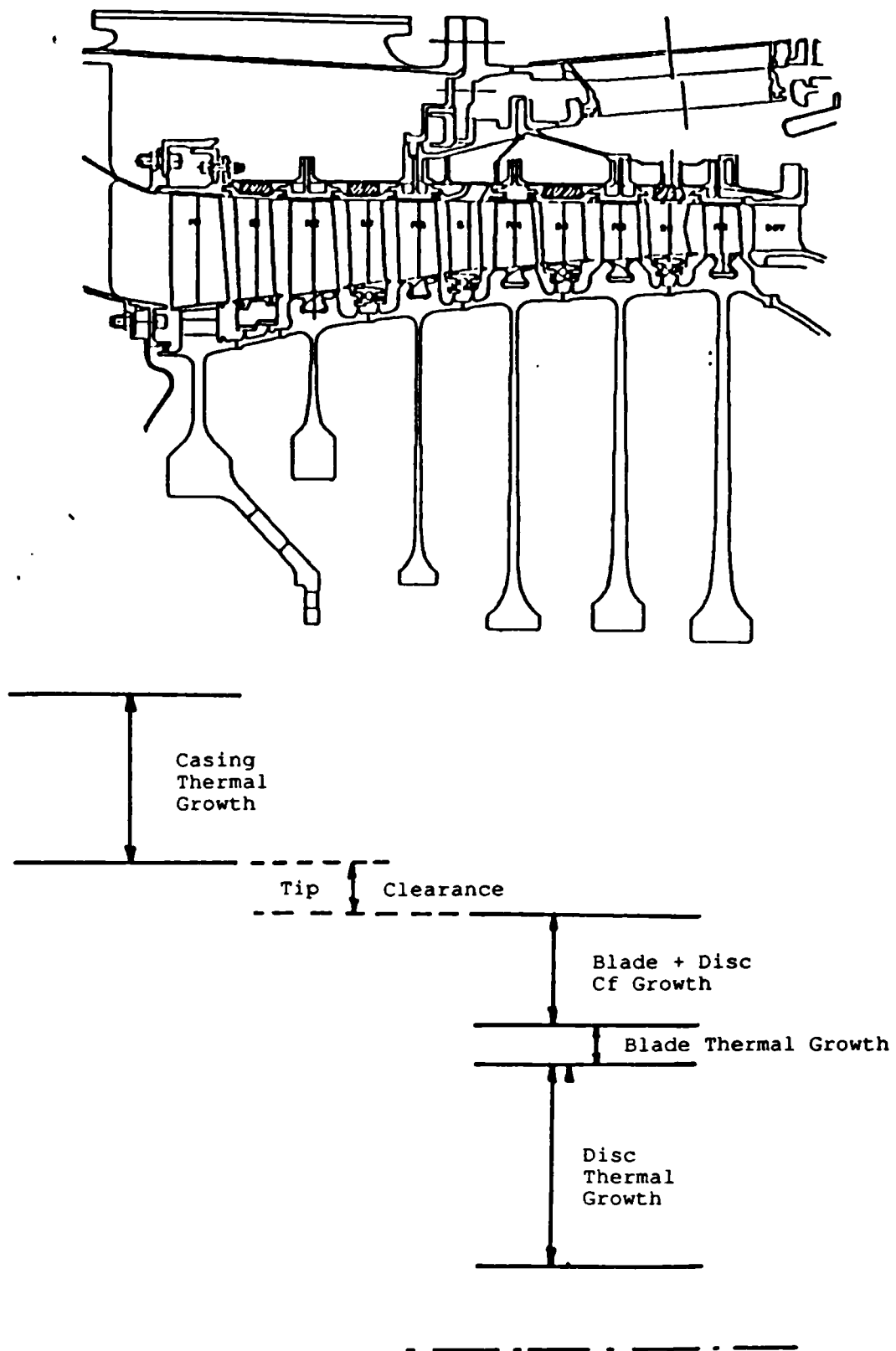


Figure 6.10 Constituent Growths Affecting Blade Tip Clearance.

$$\Delta R = R \alpha \Delta T$$

where R = casing radius (mm)

α = linear coefficient of thermal expansion
for casing material (mm/mm deg.C)

ΔT = casing temperature above datum (288K)

Blade and disc centrifugal, (cf), growth factors were obtained from the Stress Office model and scaled by the rotor speed squared to give predicted cf growths. Also blade and disc thermal growth curves were obtained from the Technical Design area and when combined with rotor cf and the casing thermal figures, a prediction of blade clearance variations against time were obtained. Figure 6.11 shows a plot of the four measured tip clearances against time for rotor stage 5 during an engine deceleration from MTO to GI. The dotted line shows the calculated predicted variation with time of tip clearance for the same manoeuvre. The agreement between prediction and measured results in this example and in all the other cases examined was considered to be extremely good.

6.6.2 Test Results-Transient.

During the testing of the engine with the two standards of compressor casing, the quantity of data recorded was considerable. It is not proposed to present all the data collected during the investigation as the majority of it is not relevant to the evaluation of the fm capacitance tip

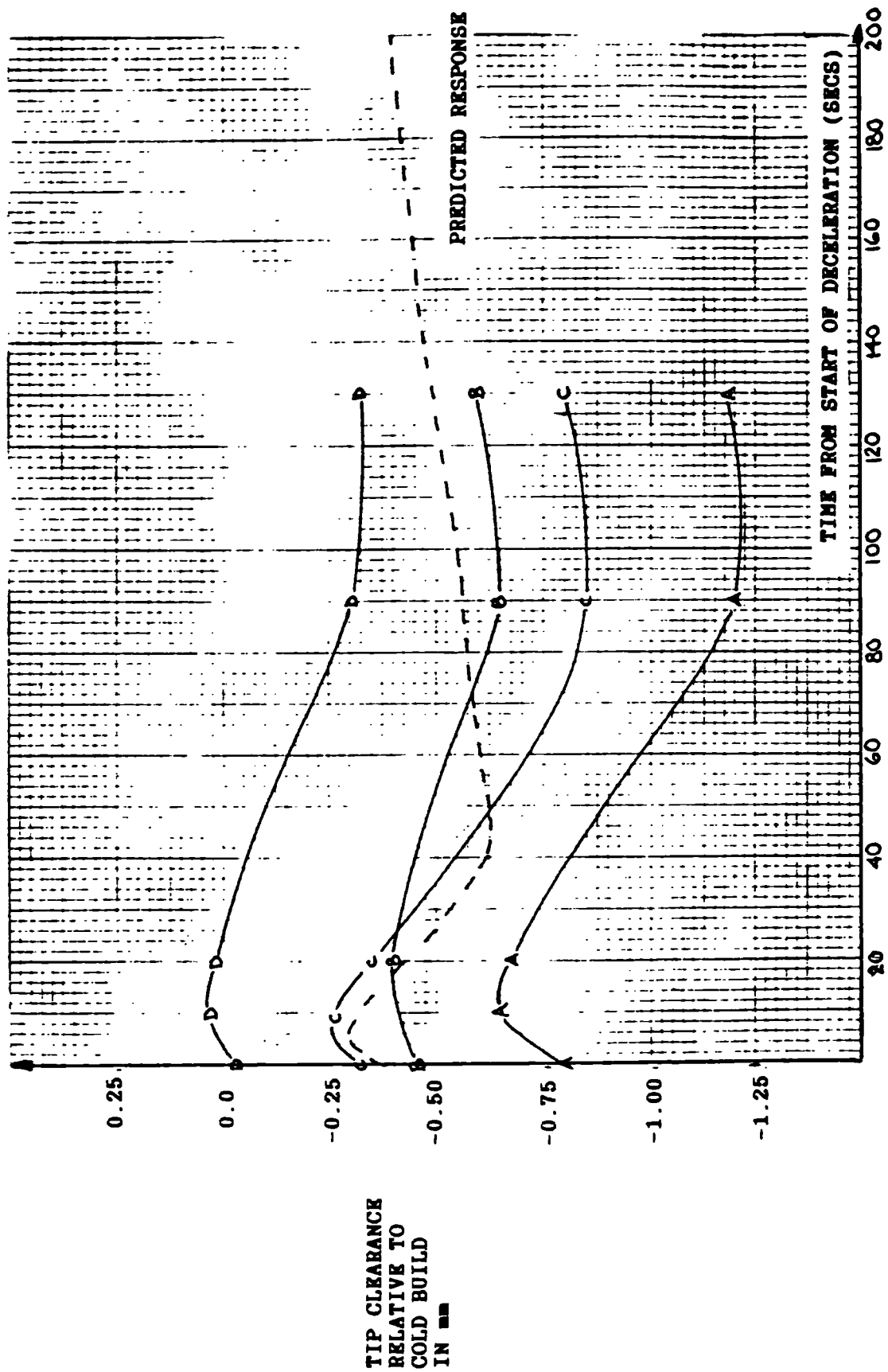


Figure 6.11 Comparison of Theoretical and Measured Tip Clearances.

clearance measurement technique. The full presentation and analysis of the test data are contained in various internal Rolls-Royce reports, (Refs.30,31,32 and 33).

A typical plot of tip clearance data is shown in Figure 6.12 and serves to show very clearly the factors which affect blade tip clearances. It was obtained from the later standard of compressor casing when operating the engine through the simulated flight cycle. The top trace represents the engine HP rotor speed plotted against time on the X-axis. The distinct phases of take-off, climb, cruise etc. are identified. The plots below the speed trace represent the tip clearances for stages 2 and 5 to the same timebase as the speed plot.

During the first acceleration of the engine as the shaft speed increases there is an initial reduction in tip clearances due to the rapid cf growth of the discs and blades exceeding the thermal growth of the casing. As the thermal response of the casing is faster than that of the rotor, the tip clearances then increase, generally reaching values greater than the cold build clearances. At around 40 to 80 seconds from the start of the acceleration the rate of heating of the disc bores allows the disc rims to grow at a faster rate than the casing. After 60 seconds, the casing temperatures fully stabilise and the tip clearances gradually reduce as the bores reach stabilised conditions and allow full growth of the disc rims.

The curves of the tip clearances during the engine deceleration show the opposite effects. An initial increase in tip clearance as the cf growth of the discs and blades reduces

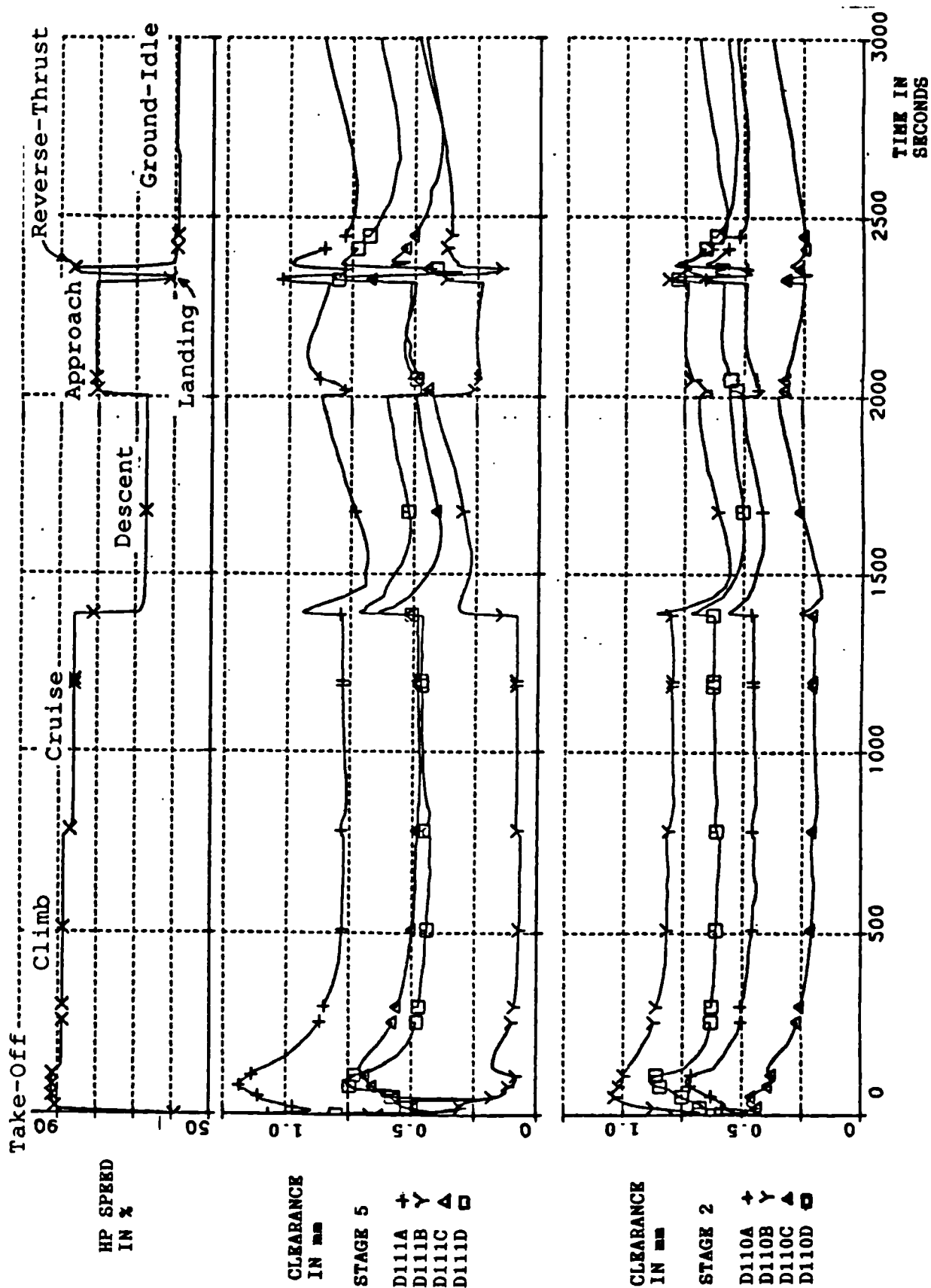


Figure 6.12 Tip Clearance Measurements During Flight Cycle.

directly with speed. This is followed by a decrease in clearances as the casing cools and contracts faster than the rotor and finally a gradual increase in clearance again as the disc bores cool and restrain the disc rims.

The hot re-slam acceleration of the engine which typically occurs on selection of reverse thrust on landing results in the occurrence of minimum tip clearances due to a combination of hot rotor discs and cool casings.

In order to fully understand the changes in tip clearance with engine condition, time and casing circumferential position, circular plots were generated. Examples of these are shown in Figures 6.13 to 6.16 which are readings taken at specific times. For the acceleration, the tip clearances are plotted 50 seconds into the manoeuvre when they appear to be at maximum values. For the deceleration, the condition of minimum clearance was chosen which occurred approximately 90 seconds after the start of the manoeuvre. The plots of the hot re-slam acceleration were made when the tip clearances read minimum values and are shown in Figures 6.17 and 6.18 for rotors 2 and 5 respectively. To observe the gross steady state casing distortions , flight idle, (FI) and MTO conditions were studied, the circular plots corresponding to these conditions are shown in Figures 6.19 and 6.20.

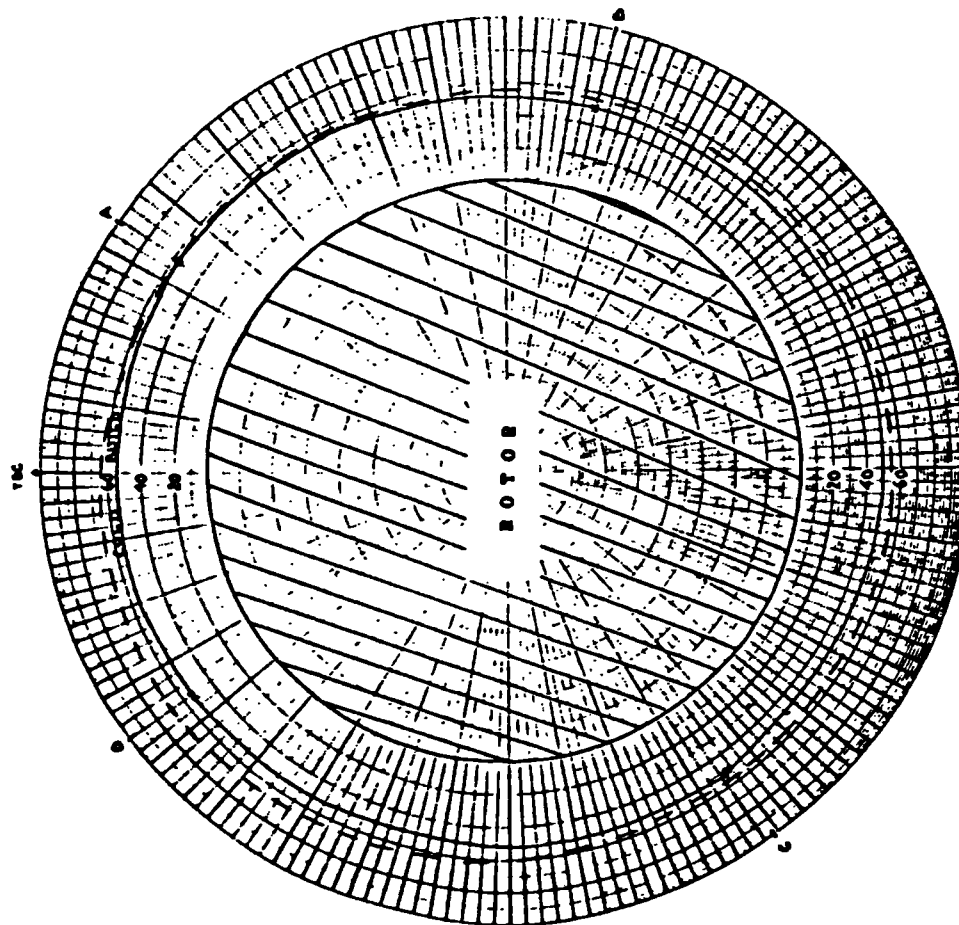


Figure 6.13 Circular Plot of Clearance
Accel/Stage 2.

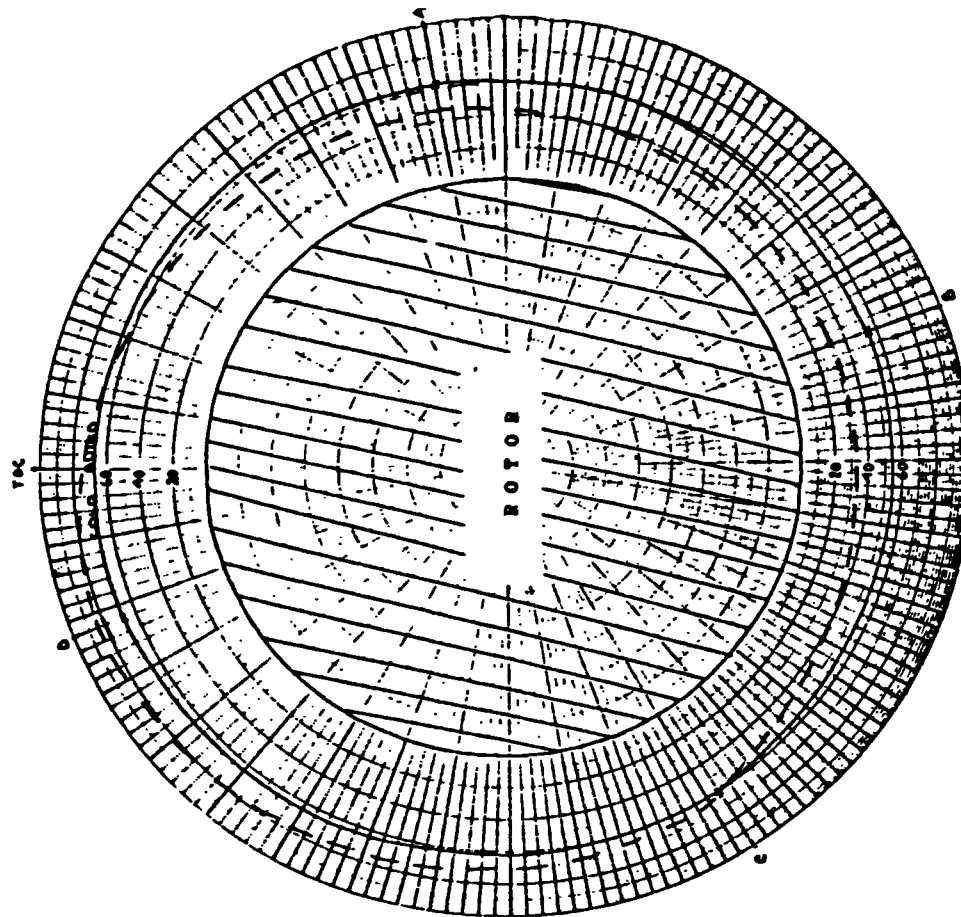


Figure 6.14 Circular Plot of Clearance
Accel/Stage 5.

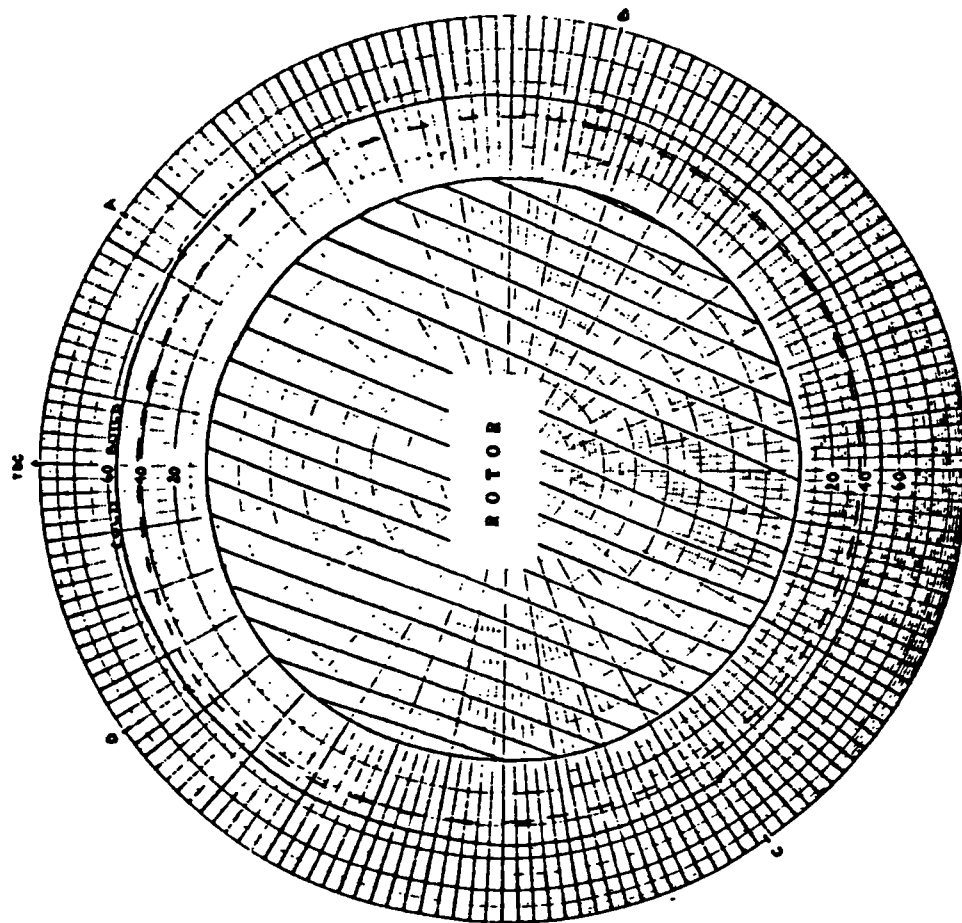
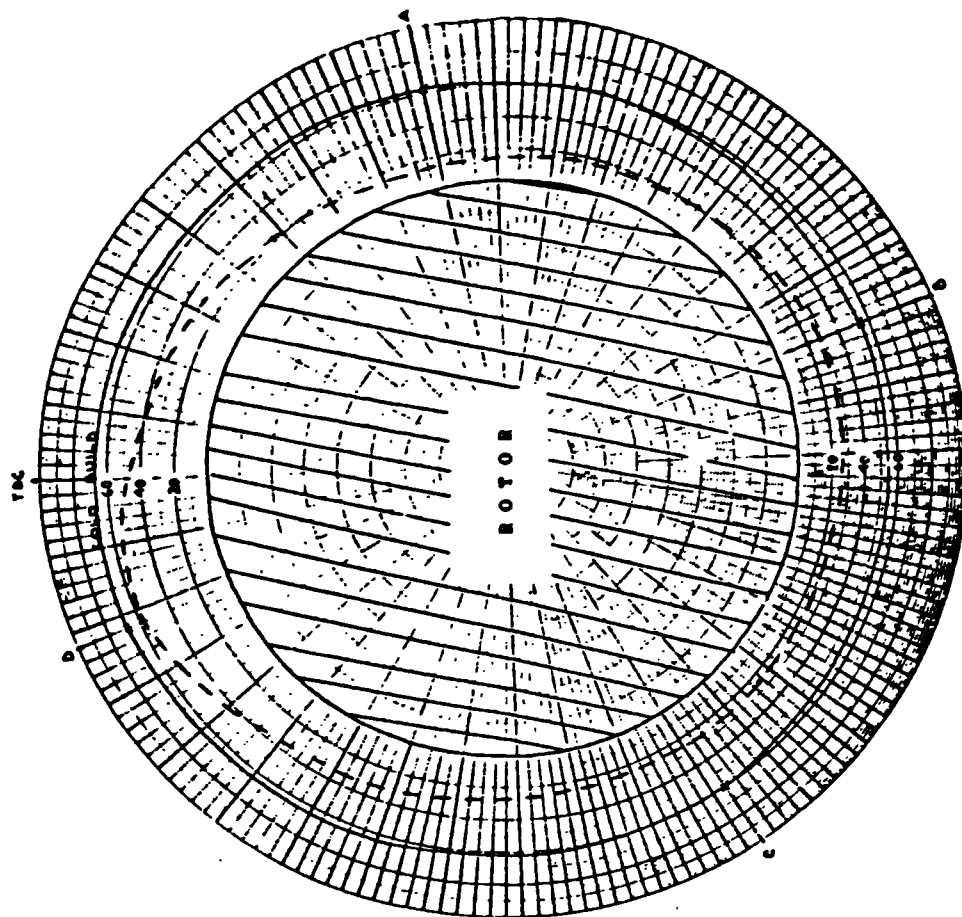


Figure 6.15 Circular Plot of Clearance
Decel/Stage 2.



— COLD BUILD
- - - MIN. CLEARANCES
90 SECS. INTO DECEL.

Figure 6.16 Circular Plot of Clearance
Decel/Stage 5.

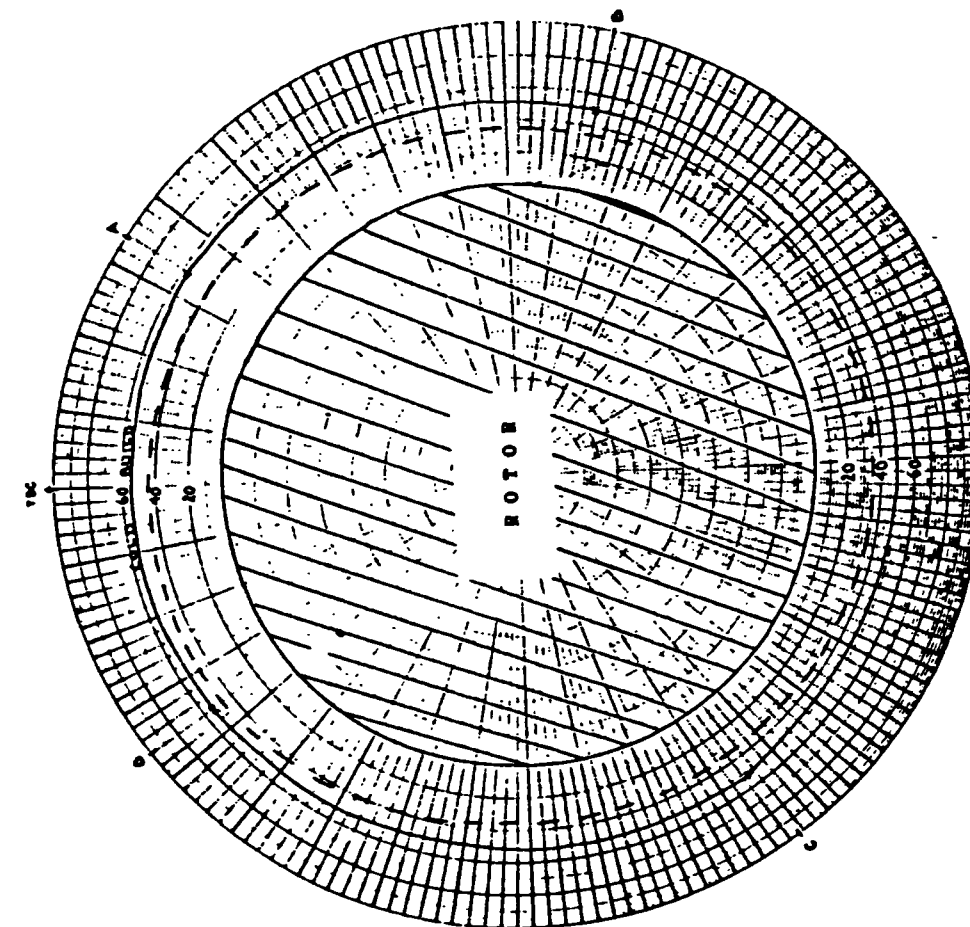


Figure 6.17 Circular Plot of Clearance

Hot Re-slam/Stage 2.

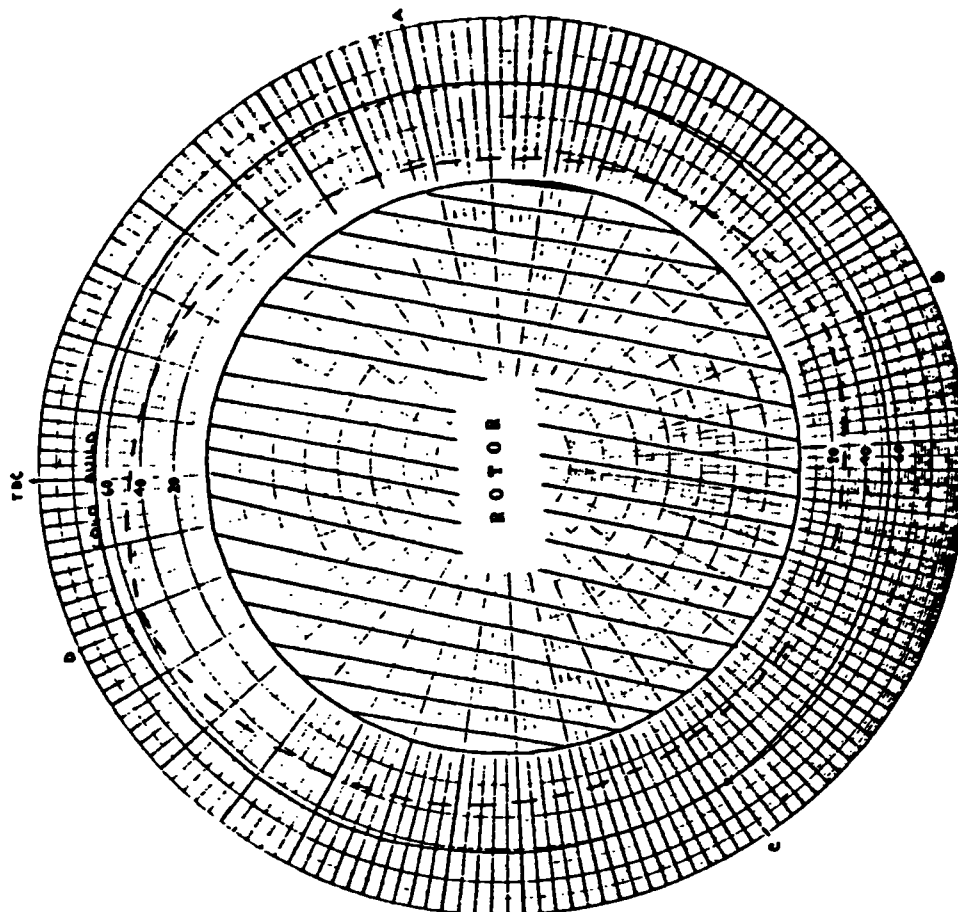
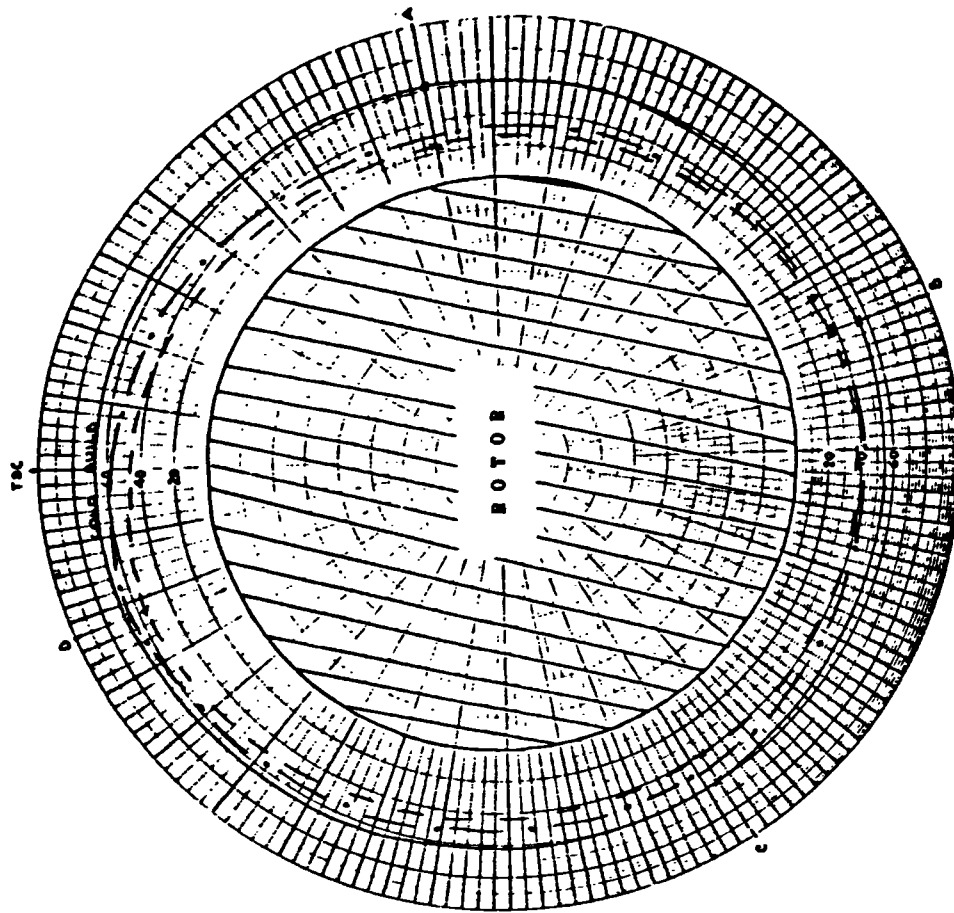


Figure 6.18 Circular Plot of Clearance

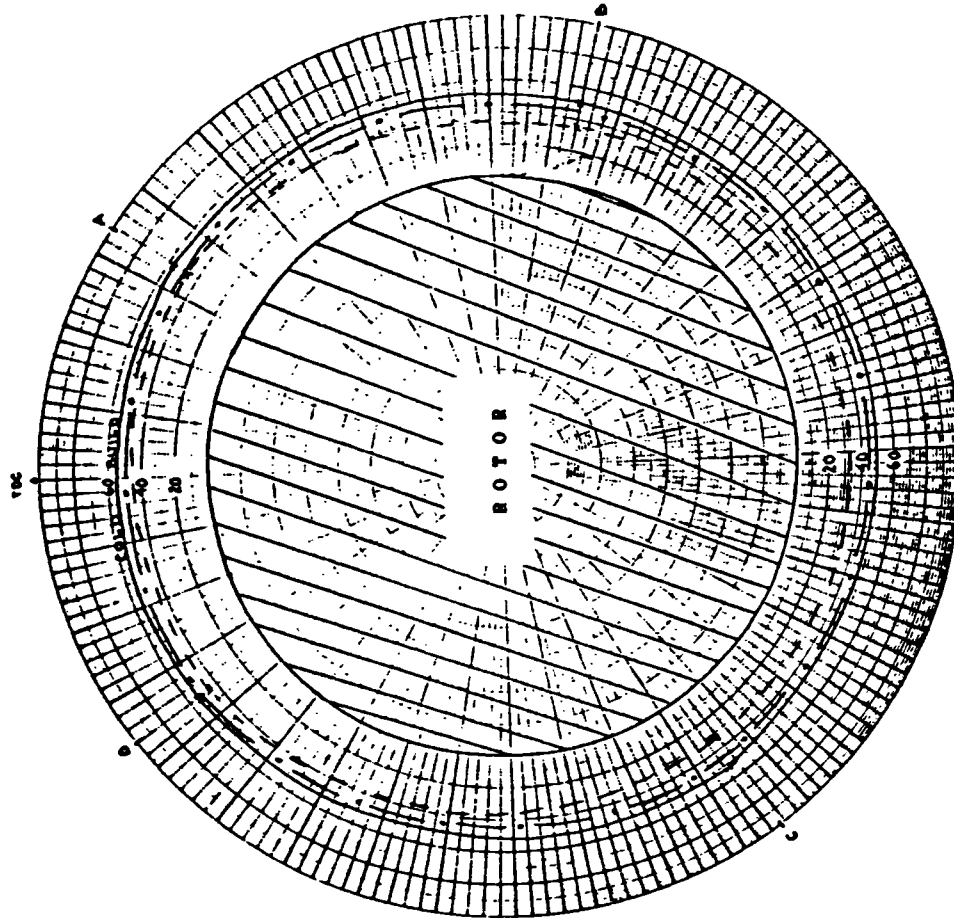
Hot Re-slam/Stage 5.



— COLD BUILD
 - - FLIGHT IDLE
 - . - . MAX. TAKE-OFF (NTO)

Figure 6.20 Circular Plot of Casing Distortions

-Stage 5.



— COLD BUILD
 - - FLIGHT IDLE (FI)
 - . - . MAX. TAKE-OFF (NTO)

Figure 6.19 Circular Plot of Casing Distortions

-Stage 2.

6.6.3 Test Results-Dynamic.

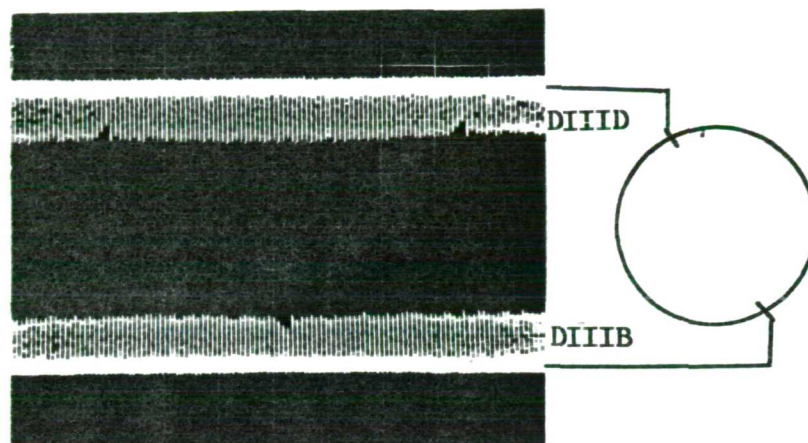
During the engine testing whilst the rms output from each channel of clearance measurement was being recorded, the blade passing signals from the probes were being monitored at the demodulator output sockets using an oscilloscope. When the HP compressor was being built, two stage 5 rotor blades were shortened in length, one by 0.25mm and the other by 0.125mm. Figure 6.21 shows two photographs of the blade passing signals from two stage 5 probes, D111B and D111D, and the two cropped blades are very visible. Both photographs were taken at GI, the difference between them being the temperature of the engine. The first photograph was taken with a cold engine and a mean clearance of 1.25mm and the second with a hot engine after running at MTO conditions and a mean clearance of 0.94mm.

At rotor speeds of less than 70%NH, the blade height profile was quite flat apart from the two cropped blades. At speeds above 70%NH during both engine tests the blade height profile occasionally changed to a sinusoidal nature. This cyclic variation was observed to have two modes :-

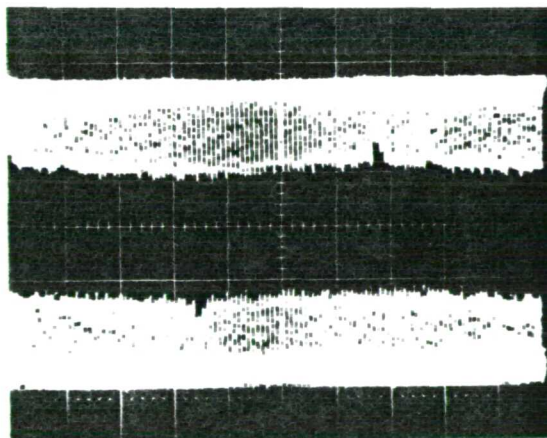
* The cyclic blade height profile was synchronous with HP speed and occurred at a rate of once per revolution. The profile thus appeared stationary when triggering the oscilloscope from the same point on the rotor. The maximum clearance which corresponds to the minimum signal level occurred approximately where the two cropped blades were positioned. Figures 6.22 and 6.23 show the modulation of tip clearance at three different speeds and

PROBE OUTPUTS OVER $1\frac{1}{2}$ ENGINE REVOLUTIONS

AT GROUND IDLE BEFORE RUNNING AT MAX CONDITIONS



THE SAME PROBES AT GROUND IDLE AFTER RUNNING AT MAX. CONDITIONS



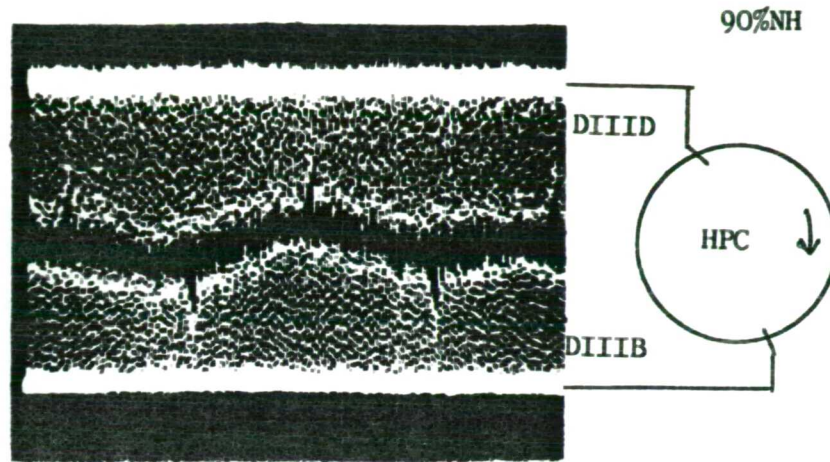
THE TOP TRACE ON BOTH PHOTOS HAVE BEEN INVERTED

Figure 6.21 Blade Passing Signals at GI.

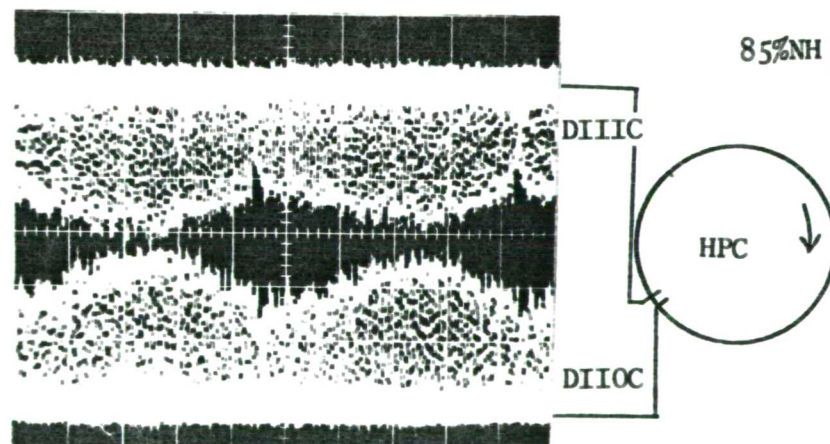
PROBE OUTPUTS OVER APPROX. TWO ENGINE REVOLUTIONS

THE BLADE HEIGHT PROFILE IS TIED TO 1ST ORDER HP. THERE IS A 180° PHASE DIFFERENCE BETWEEN PROFILES* FROM PROBES LOCATED OPPOSITE EACH OTHER IN THE CASING.

NOTE THE TWO SHORT BLADES AT THE TROUGH OF THE WAVE SHAPED BLADE PROFILE.



THE BLADE HEIGHT PROFILE FROM PROBES LOCATED IN A SIMILAR CIRCUMFERENTIAL POSITION ARE IN PHASE* AS SHOWN BELOW.

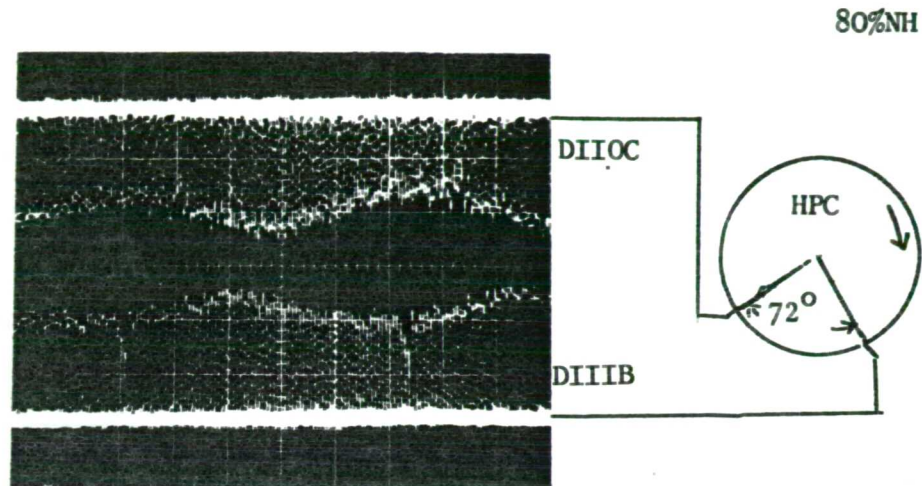


* THE TOP TRACE ON BOTH PHOTOS HAVE BEEN INVERTED TO ALLOW PHASE COMPARISONS TO BE MADE

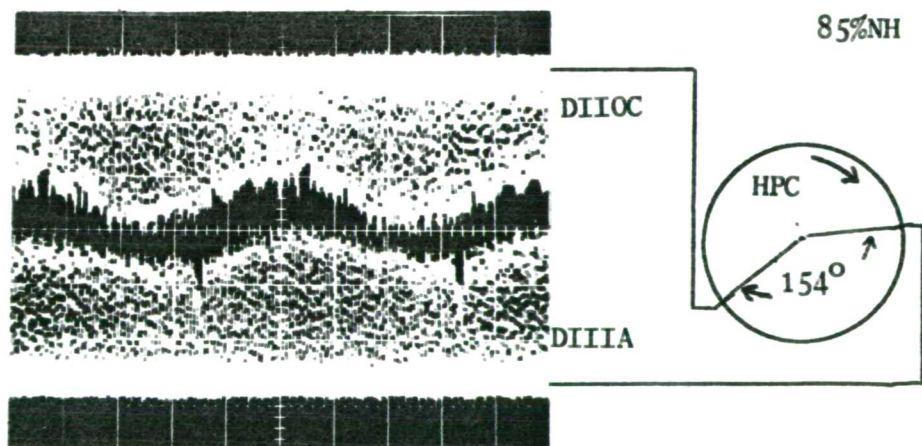
Figure 6.22 Modulation of Blade Passing Signals

PROBE OUTPUTS OVER APPROX TWO ENGINE REVOLUTIONS SHOWING:

THE PHASE DIFFERENCE BETWEEN THE TWO BLADE HEIGHT PROFILES IS APPROX. 1 SQUARE ON THE BACKGROUND SCALE. ONE REV TAKES 5.3 SQUARES. THE PHASE ANGLE BETWEEN THE TWO PROFILES IS $\frac{1}{5.3} \times 360^\circ = 68^\circ$. THIS AGREES WELL WITH THE ANGULAR DISPLACEMENT BETWEEN THE PROBES OF 72° .



THE PHASE DIFFERENCE THIS TIME IS APPROX 2 SQUARES. ONE REV. TAKES 4.9 SQUARES. PHASE ANGLE BETWEEN THE PROFILES = $\frac{2}{4.9} \times 360^\circ = 147^\circ$. COMPARES WELL WITH THE ANGULAR DISPLACEMENT BETWEEN THE PROBES OF 154° .



THE TOP TRACE ON BOTH PHOTOS HAVE BEEN INVERTED TO ALLOW PHASE COMPARISONS TO BE MADE.

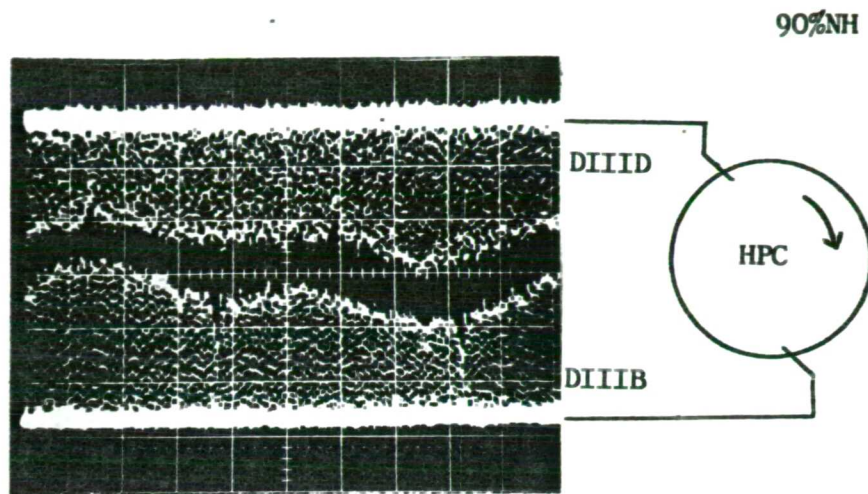
Figure 6.23 Modulation of Blade Passing Signals

compares both stage 2 and stage 5 probes. The phase relationship of any two clearance signals corresponded exactly with the circumferential angular spacing of the probes on the compressor casing.

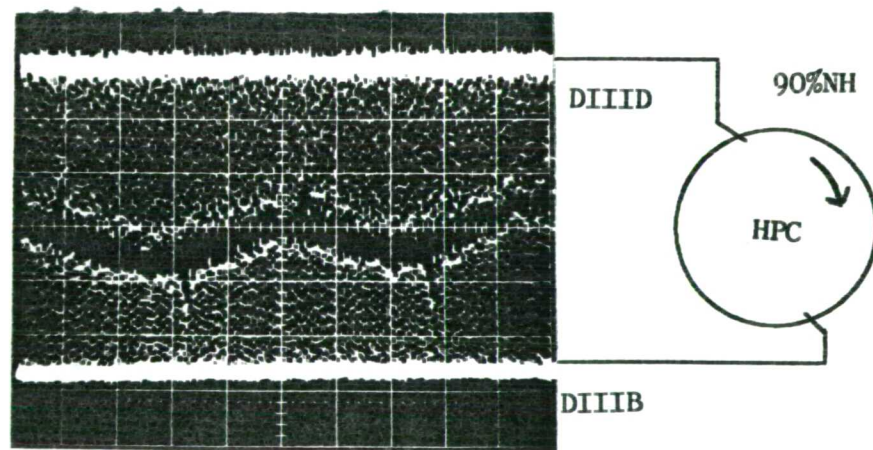
* The cyclic blade height profile was still evident but was modulated by a lower frequency movement, approximately first order LP rotor speed frequency or half HP rotor speed frequency. Figure 6.24 shows two photographs of the blade passing signals from probes D111B and D111D separated by 30 seconds.

In all cases the modulation amplitude of the blade height profiles was estimated to be equivalent to a clearance variation of less than 0.15mm.

PROBE OUTPUTS SHOWING THE NORMALLY 'STATIONARY' BLADE HEIGHT PROFILE BEING MODULATED BY A LOWER FREQUENCY (PROBABLY FIRST ORDER FAN) MOVEMENT. .



TIME DIFFERENCE BETWEEN PHOTOS - 30 SECS



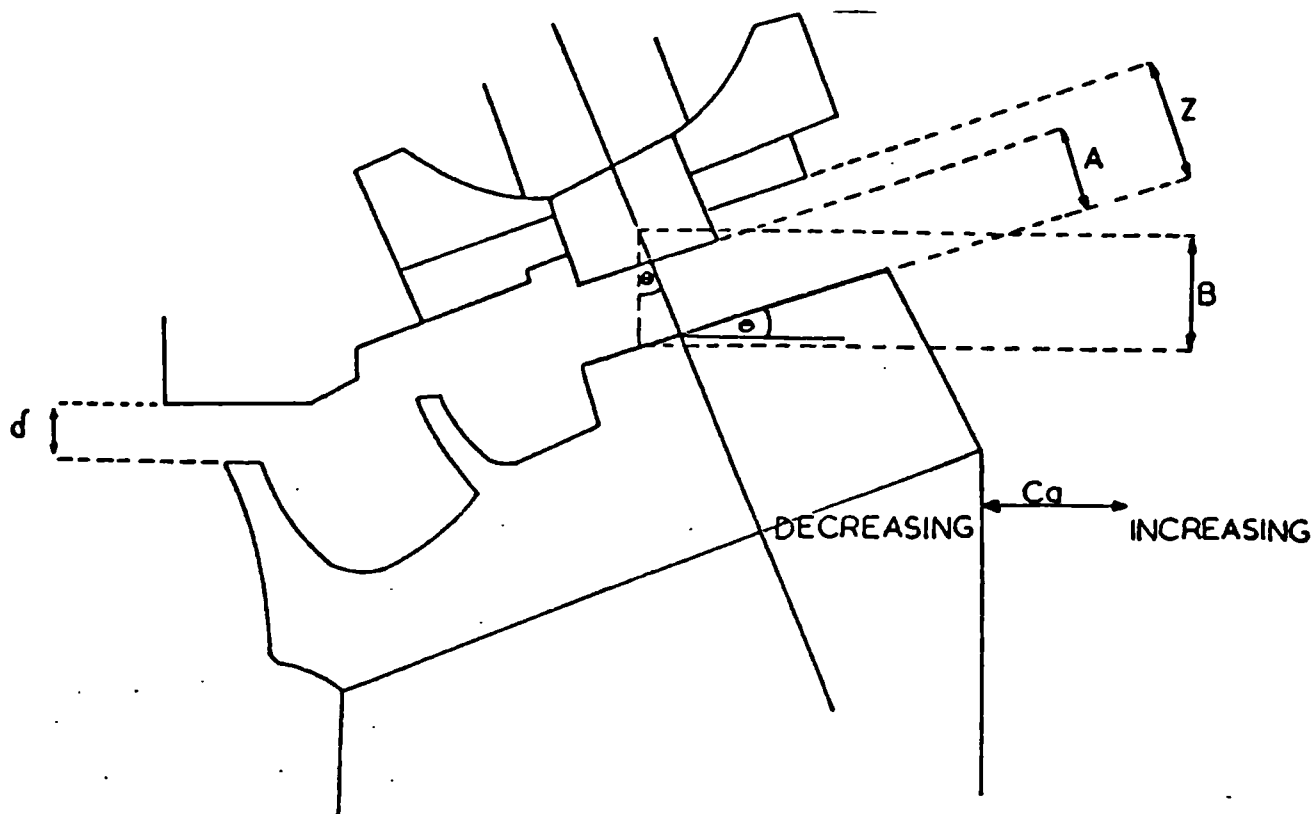
THE TOP TRACE ON BOTH PHOTOS HAVE BEEN INVERTED TO ALLOW PHASE COMPARISONS TO BE MADE.

Figure 6.24 Non-Synchronous Modulation of Blade Passing Signals.

7.0 CLEARANCE SYSTEM EVALUATION: ENGINE TURBINE.

7.1.0 Introduction.

Following the successful use of the fm capacitance blade tip clearance measuring probes on an engine HP compressor, measurements were required of turbine blade tip clearances. This data would provide a method of verifying mathematical modelling of the turbine and shroud segment transient movements. The instrumentation specification, as stated by the Technical Design Department, required the measurement of the radial and axial movements of both the HP and IP turbine blade tips. Axial tip movement measurements were required, in addition to the radial measurements, because the blade tips were not parallel to the engine centreline. Both the HP and IP turbine blade tips had "hade" angles of 10 degrees, ie they were angled at 10 degrees to the engine centreline. This implied that the radial clearance measurements would have an axial movement dependency. Therefore, the radial movements were subject to axial movement corrections. Figure 7.1 shows the relationship between the clearance as measured by the fm capacitance probes, (A), the blade hade angle, (θ), the axial movement of the turbine blade tips, (Δa) and the radial clearance between the blade and the shroud segment, (B). Although these corrections affect the absolute values of the radial measurements, they do not affect any out of roundness or eccentricity displayed by the probes. Out of roundness is where the shroud segments are not round when compared with the rotor tip radius. Eccentricity is where the shroud segment and



- Z CLEARANCE BETWEEN HONEYCOMB AND FENCE
 A CLEARANCE MEASURED BY PROBE
 Z-A PROBE IMMERSION (IM)
 B RADIAL CLEARANCE BETWEEN HONEYCOMB AND FENCE
 Ca AXIAL MOVEMENT
 d FRONT FIN RADIAL CLEARANCE

$$\text{CORRECTED RADIAL CLEARANCE} = \frac{(A+IM)}{\cos \theta} + \Delta Ca \times \tan \theta$$

FENCE TO HONEYCOMB

Figure 7.1 Correction of Radial Probe Data for Axial Movement.

rotor centres are not coincident. Both these effects give asymmetry in the turbine which can cause :-

- * Over-tip gas leakage.
- * Inner and outer annulus spoiling.
- * Air seal misalignment.

Each of the above degrade the performance of the turbine and increase the specific fuel consumption of the engine.

Axial movements are governed by relative thermal and load induced movements of the structures between the location bearings, situated towards the front of the engine and the shroud segments and turbine blades respectively. Additional relative axial movements can come from bending of the turbine disc diaphragms and rims and any blade movements. Pressure effects on the shroud segments can cause movements due to design clearances.

The radial movements are governed by the same factors which were considered in the HP compressor tip clearance investigation, ie relative cf, thermal and load induced movements of the discs, blades and shroud segment locating structures.

In order to fully understand these axial and radial displacements, in addition to the tip clearance measurements, the experiment required the measurement of approximately 200 temperatures, both metal and air and the measurement of a casing to compressor disc movement.

In Chapters 2.5.0 and 3.6.0 the use of a carrier driven guarded capacitance measurement technique in a hot turbine environment was considered to be a practical proposition. Thus for the HP and IP radial clearance measurements the fm capacitance measuring probes were specified with a high level of confidence.

7.2.0 Turbine Blade Tip Geometry.

The fm capacitance clearance system, as designed, has a lower frequency response limit of approximately 30 Hz., hence the need to calibrate against a rotating target. Both the HP and IP turbine blades used in the engine under investigation were of a shrouded design. In a shrouded turbine design, the tips of the blades, when assembled into a rotor, form a continuous ring which acts as a very efficient seal preventing the leakage of gas over the blade tips. The HP turbine blade tip design is as shown in Figure 7.2. Each blade has an aerodynamic feature, referred to as a "fence", which provides, by chance, an almost perfect target for the capacitance measuring probes, similar to the unshrouded compressor blade tips.

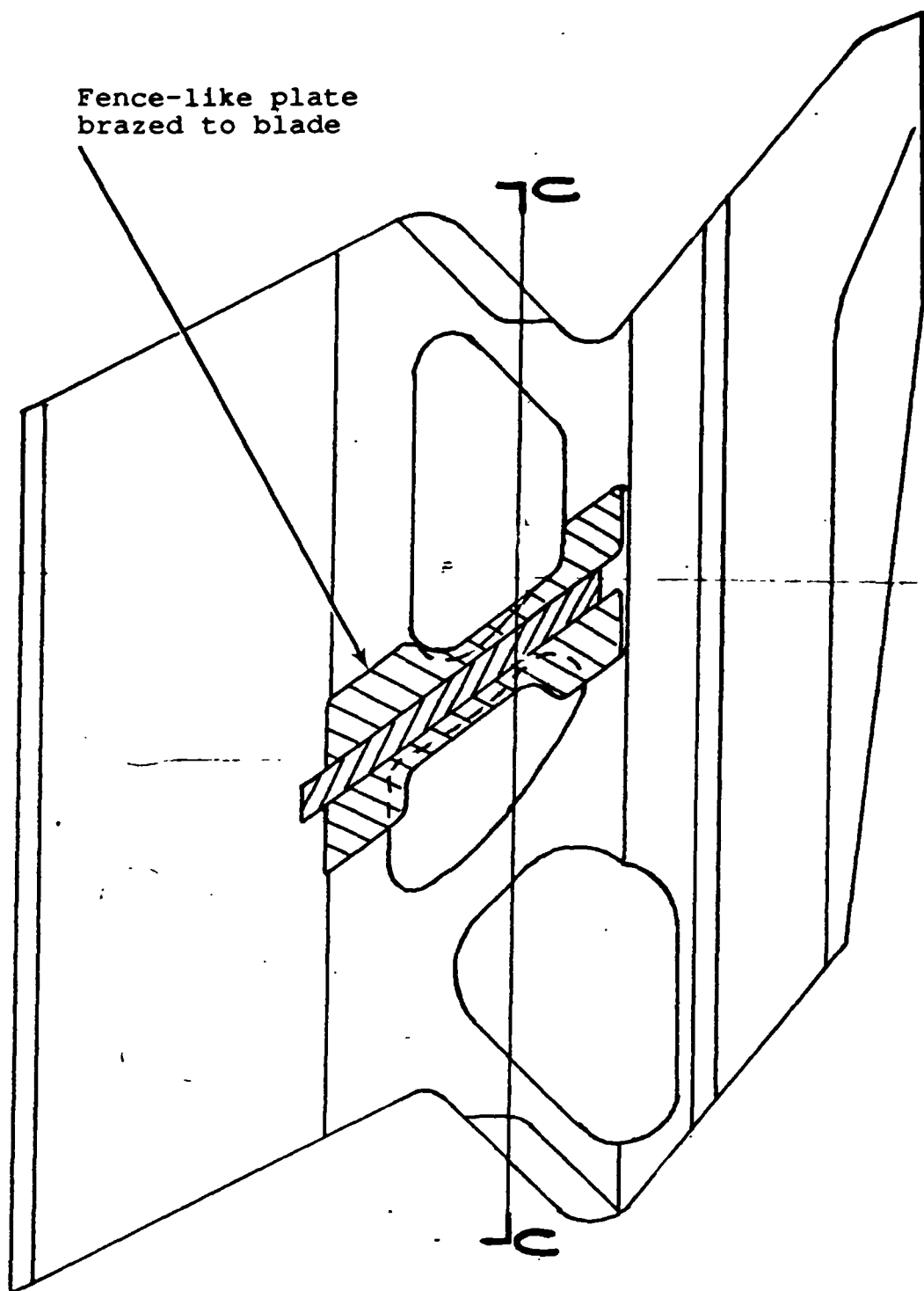
The IP turbine blade tip design however is different in that the fence is missing and three circumferential sealing fins are substituted as shown in Figure 7.3. The solution which was adopted consisted of removing completely the central sealing fin from each blade tip and brazing in its place a fence-like plate. A view of a modified IP turbine blade tip is shown in Figure 7.4.



Figure 7.2 HP Turbine Blade Design.



Figure 7.3 IP Turbine Blade Design.



VIEW OF IP. TURBINE
BLADE SHROUD

Figure 7.4 Modified IP Turbine Blade.

7.3.0 Radial Clearance Probe Installation.

The major consideration in the adaptation of the HP compressor design of fm capacitance probe for use in a turbine environment was that of the higher temperatures. The two areas of concern were :-

- * The integrity of the measuring probe sensor. The maximum working temperature of the gold-based braze used to assemble the alumina bead insulator to the sensing electrode and the probe body was estimated to be 950K. This compares with expected casing metal temperatures of 1100K and gas temperatures of 1500K.

- * The measuring probe modulator circuitry was designed to operate reliably up to a maximum temperature of 370K. The under cowl temperatures in the turbine region of an engine could be as high as 500K. During the HP compressor investigation described in section 6.0, the air cooling of the modulators proved to be barely adequate.

The proposed solution to the anticipated temperature problems consisted of cooling the measuring probe sensor with high pressure air which would surround the brazed assembly before venting into the turbine gas path. This cooling would have the additional benefit of protecting the insulating surface from possible contamination by combustion products. The modulator would be cooled by surrounding it with a jacket supplied with cold water.

The installation design for the HP probes is shown in Figures 7.5 and 7.6, the IP installation being similar. Figure 7.5 shows a sectioned view of a measuring probe (section BB) and a section of the probe installed in a water jacket. Section LL and section BB repeated show the water jacket inlet and outlet connections and the air connection respectively. An enlarged view of the probe end location is shown in Figure 7.6. It can be seen that the radial location of the measuring probes is provided by spherical seatings (item 126), the absolute value of radial immersion being adjusted by the thickness of the washer (item 125). The spherical seatings enabled differential axial movements to occur between the shroud segments and the turbine casing, as predicted by the theoretical model of the turbine structures, when the tip clearance measuring probes were installed. A mounting arrangement which did not permit these movements to occur freely would almost certainly have resulted in distorted measuring probes and meaningless measurements.

The measuring probes were loaded against the spherical seatings on the shroud segments by means of coil springs in the retaining cap (items 48 and 51 in Figure 7.5) with a force of 36kg. This arrangement allowed for differential radial movements to occur between the turbine casing and the shroud segments.

The requirement was for a total of ten radial tip clearance measurements, five from the HP turbine and five from the IP turbine. Figure 7.7 shows schematically the circumferential location of both the radial and axial displacement probe.

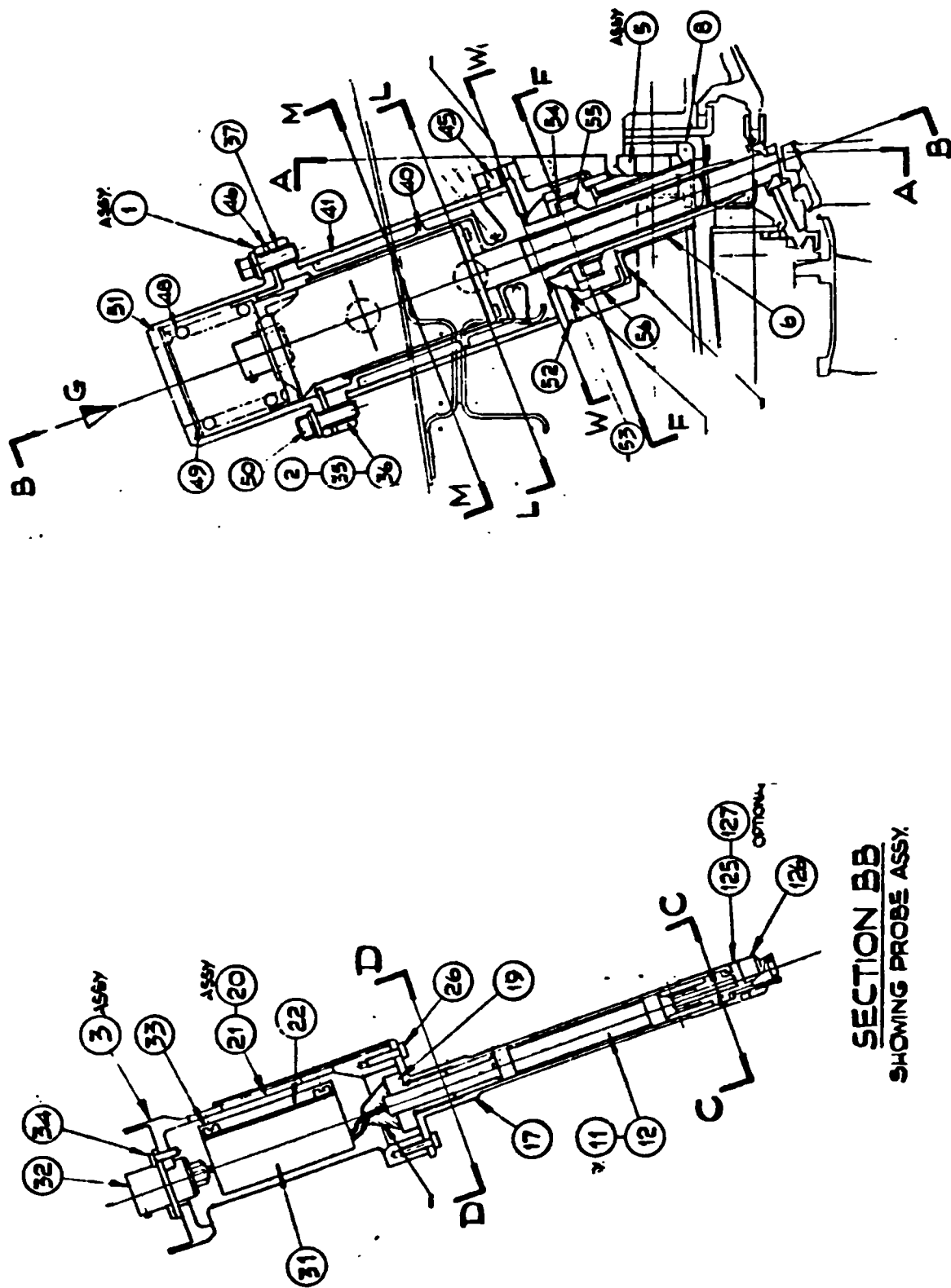


Figure 7.5 Section of HP Radial Probe and Water Jacket Installation.

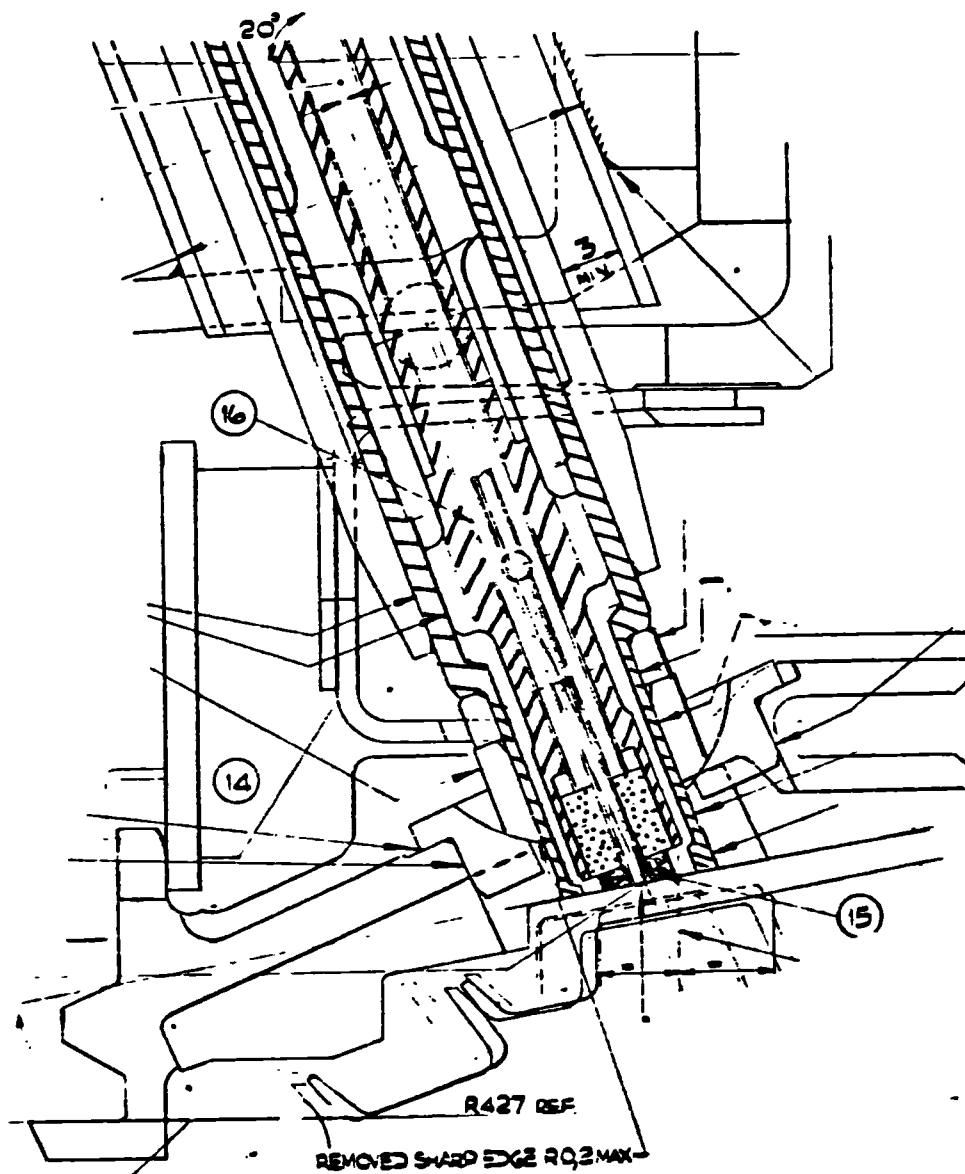


Figure 7.6 Enlarged View of HP Turbine Probe End Location.

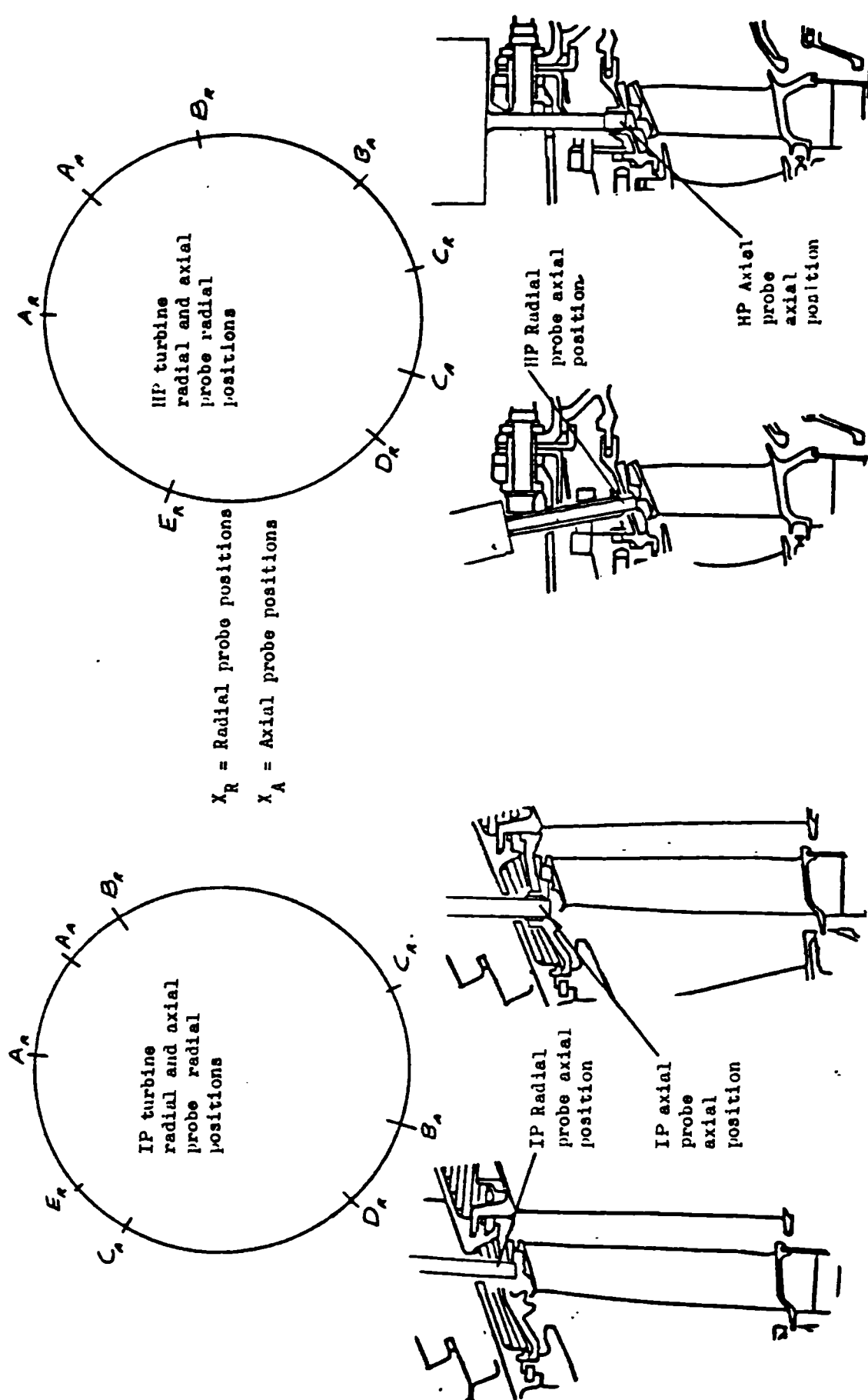


Figure 7.7 Location of IP and HP Turbine Radial and Axial Probes.

7.4.0 Radial Clearance Probe Calibration.

7.4.1 Calibration Equipment.

The requirement to calibrate the tip clearance measuring probes with the assigned demodulators against the particular target blades was similar to that in the evaluation of the system on the engine compressor. However the tips of the IP turbine blades had been modified to make them suitable for use with the fm capacitance probes. The modification had created a unique probe target geometry and the operational implications of this situation were such that a different calibration routine had to be established.

Prior to completion of the engine build, the calibration of the five IP turbine radial clearance probes was possible using the actual engine IP turbine rotor as the target. Subsequent IP probe calibrations would have been impossible due to lack of access to the IP turbine. The problem was resolved by the design and manufacture of a dedicated clearance probe calibration rig. The rig comprised a variable speed electric motor driving a shaft arrangement mounted in precision bearings. To this shaft could be attached a variety of aluminium discs into the circumference of which pseudo blade tip profiles could be machined. Figure 7.8 is a photograph of the calibration rig without a calibration disc attached. A view of the rig with a calibration disc in place and a probe mounted on the traverse micrometer slide is shown in Figure 7.9.

Before the rig was accepted for the routine calibration of fm tip clearance probes, comparisons were made between

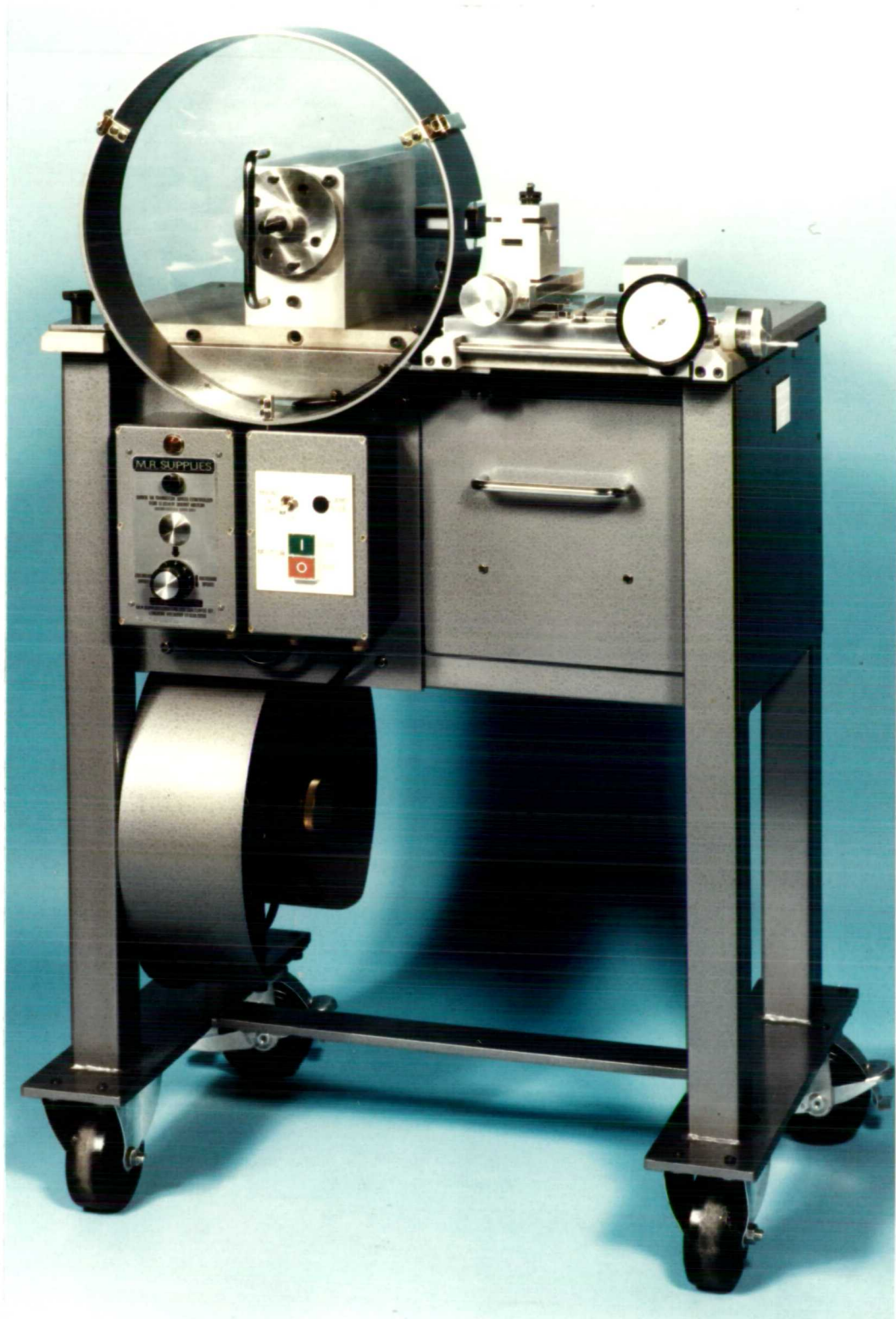


Figure 7.8 View of Capacitance Probe Calibration Rig.

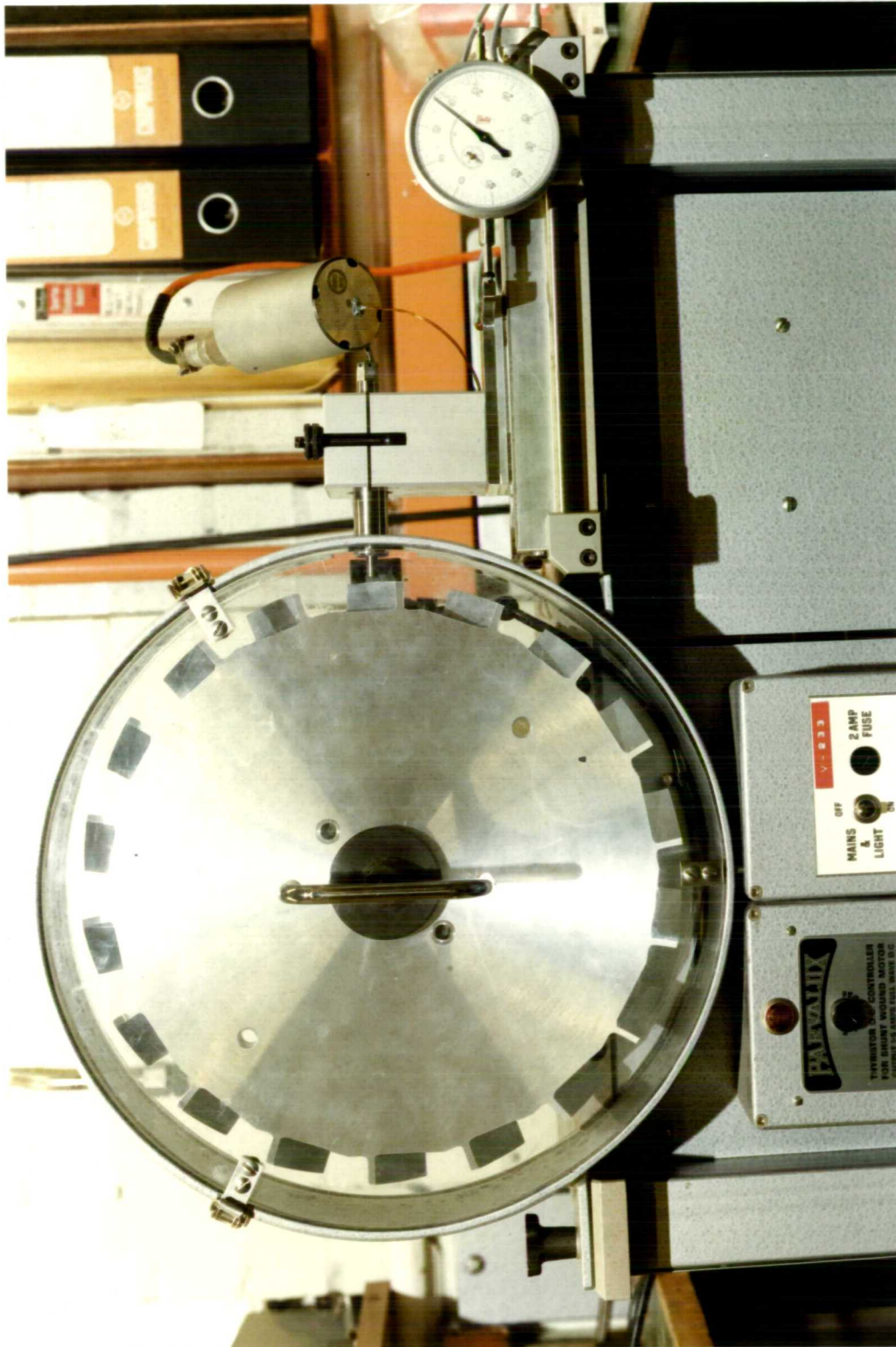


Figure 7.9 Calibration Rig with Disc and Probe.



Figure 7.10 Turbine FM Capacitance Measuring Probe.

the probes were calibrated on the rig without a segment of casing being attached.

7.4.3 Installed Radial Probe Calibration Validation.

Before the radial clearance probes were fitted to the engine, dimensional drop-checks of a similar nature to those carried out on the compressor were performed on the turbines. However, in the case of the turbine application, two special drop-check tools with spherical seatings were manufactured. This was considered essential in order to obtain accurate drop-check measurements, the tools effectively simulating the location features of the HP and IP measuring probes.

The IP turbine drop-check tool is shown in section fitted to the engine in Figure 7.11. Also shown are the dimensions A, B, C, D and Z which were required to be measured in order to calculate the probe end clearance, S, using the following relationship :-

$$S = 0.985 (C + B - D - Z) + 0.86$$

Figure 7.12 shows the check calculations which were performed when the radial tip clearance probes were fitted to the engine to ensure correct seating of the probes.

Considerable time and effort were subsequently spent performing dimensional measurements on the probes and using the drop-check tools on the HP and IP turbine installations. These measurements were then compared with the values of

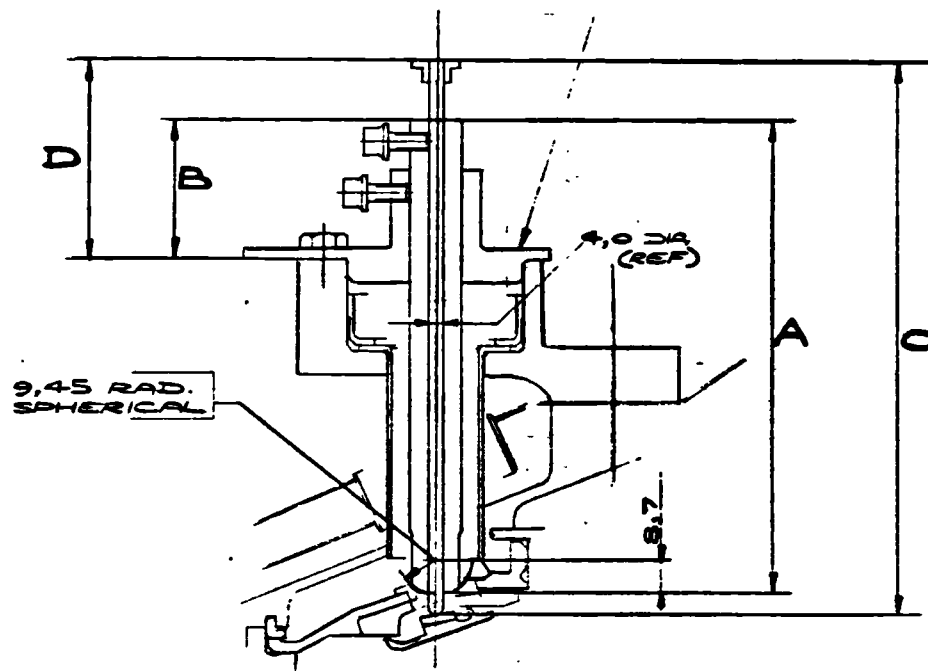
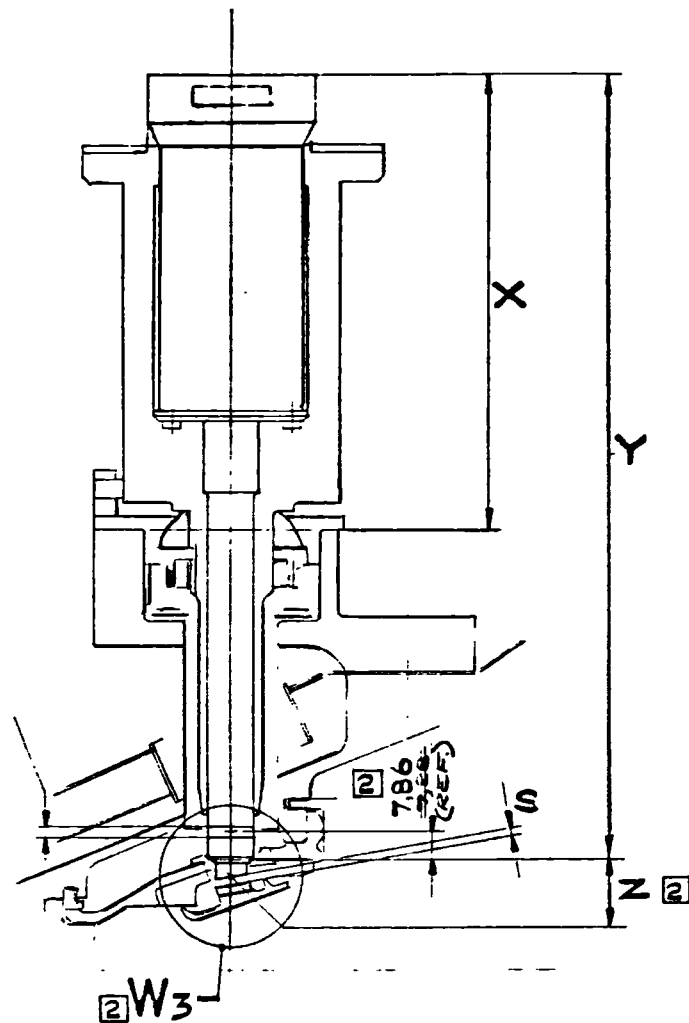


Figure 7.11 IP Turbine Radial Probe Setting Tool.



RADIAL PROBE FITTING INSTRUCTION

FIRST INSERT SETTING TOOL & RECORD DIMS. A & B
MEASURE PROBE LENGTH Y.

INSERT PROBE UNTIL IT LOCATES THEN MEASURE X
THEN CHECK BY THE FOLLOWING CALCULATION :-

$$X = Y - A + B + 0,84 \quad [2]$$

IF MEASURED X & CALCULATED X ARE WITHIN $\pm 0,5$
THEN THE PROBE IS FULLY HOME & THE SPRING &
CAP MAY BE FITTED.

Figure 7.12 IP Turbine Radial Probe Fitting Checks.

tip clearance as measured by the installed probes.

In order to generate signals from the fm capacitance probes after installation in the engine, both the HP and IP turbines needed to be rotated at a speed of approximately 60 RPM. This activity was performed in the engine pre-rig area prior to the engine being transported to the test bed. Rotation of the HP system was achieved relatively simply by manual effort via a crank connected to the external gearbox. The IP system proved more difficult to rotate as it was inaccessible when the engine was assembled. It was possible, however, to lock the IP and LP turbines together and then rotate the LP system by means of an air motor. A photograph of these rotational checks being performed is shown in Figure 7.13. The polythene sheet covering the fan intake was found to be necessary to reduce the windage effects in the LP and IP systems to a level which allowed a rotational speed of approximately 60 RPM to be achieved with a low power air motor.

After many checks of dimensions and probe calibrations, the conclusion was reluctantly reached that good agreement between the drop-check values and measured values of clearance could not be obtained. The apparent reasons for this were :-

- * The extreme difficulty of lining the drop-check tools upon the turbine blade fins.
- * Four relatively large dimensional measurements had to be made to record a small difference. The build up of errors proved to be significant in the final calculated clearance.
- * Difficulties were experienced in the fitting and use of the drop-check tools themselves.



Figure 7.13 HP and IP Turbine Radial Probe Rotational Checks.

The spin checks however, demonstrated that the measurement of the radial movement of the probes, achieved by the insertion of different thickness spacing washers, was highly accurate. These results indicated that the individual measuring probe calibrations were correct and that the absolute clearances being indicated by the measuring probes were also correct. The generally undesirable non-linear clearance probe calibration characteristic proved to be very useful in this calibration validation exercise.

The decision was made to believe the radial capacitance probe measurements and adjust the washer sizes to give the required clearances. The cooling water pipework was then attached to the probe water jackets and pressure tested prior to the engine being transported to the test bed. Figures 7.14 and 7.15 show the core engine fully dressed with the measuring probes installed and the cooling water and air manifolds.

7.5.0 Engine Test Programme.

After the engine had been rigged on the test bed and the clearance measuring probes connected to the demodulators, a number of dry cranks were performed to confirm all the instrumentation was fully operational. This was followed by starting the engine and conducting an incremental performance curve from GI to MTO to verify that both the engine and the special instrumentation were functioning as expected. One IP radial probe, D2424E, failed (the modulator) during this

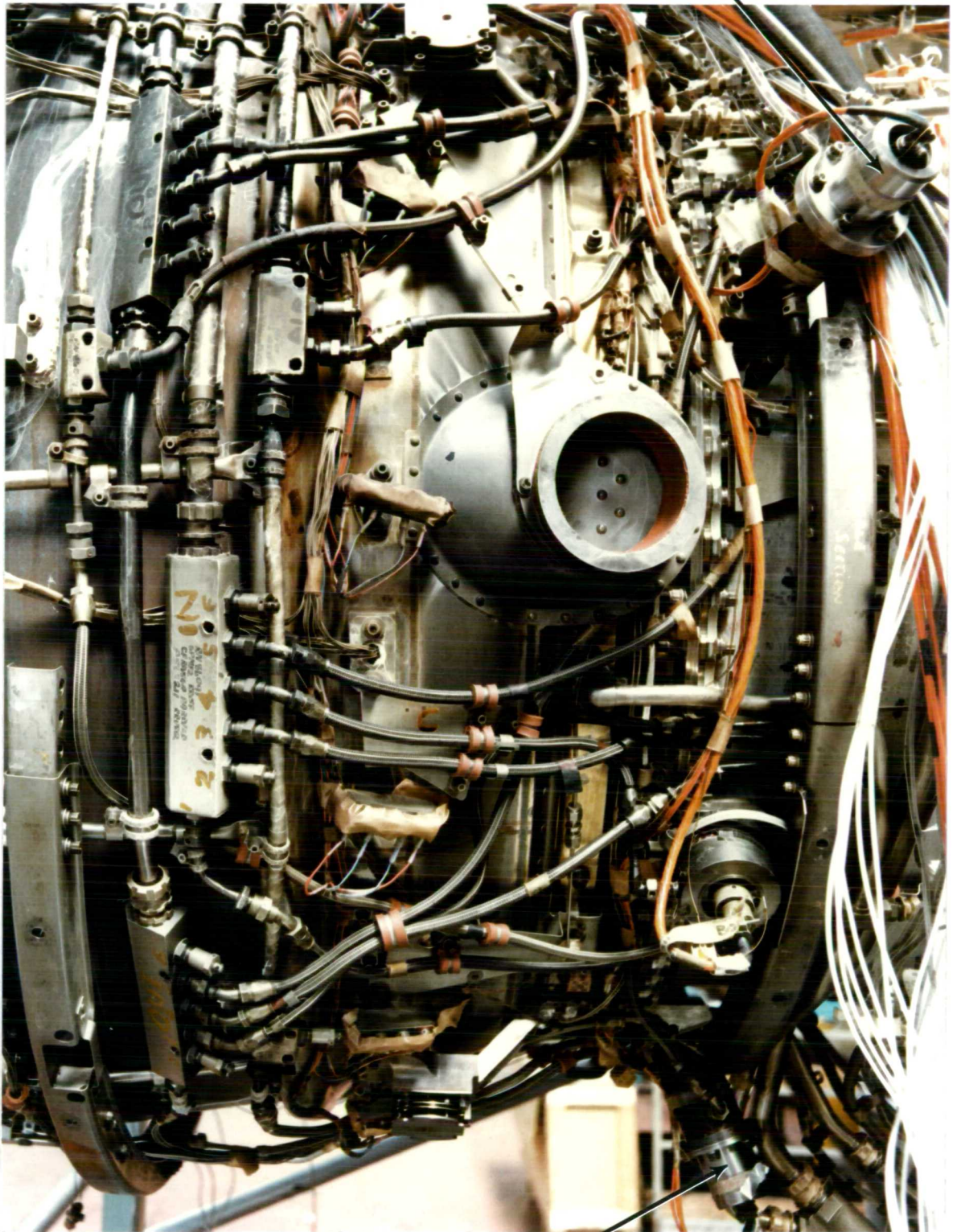


Figure 7.14 View 1 of Probe Installation on Engine.

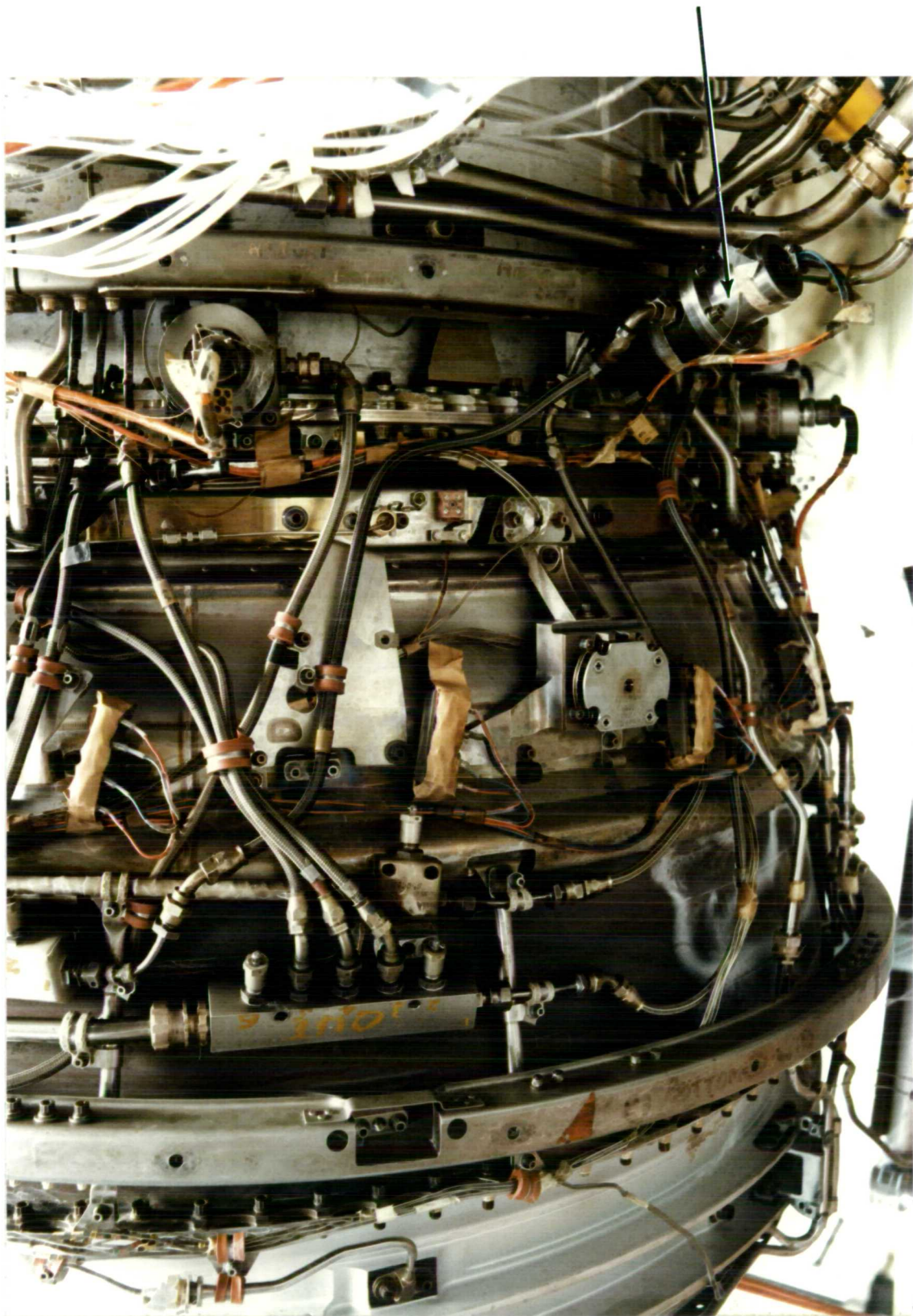


Figure 7.15 View 2 of Probe Installation on Engine.

shake-down running and was replaced with a spare probe.

Problems were also experienced with the optical axial movement measuring probes due to higher than expected levels of radiation from the turbine blade tip shrouds, particularly in the HP turbine.

Once the axial movement measuring probe problems had been resolved, the engine was dry cranked to obtain the cold datum clearance measurements. The test schedule then consisted of operating the engine through square cycles (accelerations from GI to MTO and back to GI) and simulated flight cycles as used in the engine HP compressor testing. Throughout this testing, the temperature of all the electronics modules in both the radial and axial movement measuring probes were continuously monitored to ensure that overheating did not occur. The maximum temperature recorded within any of the probes was 320K, a figure which was sufficiently low to fully justify the choice of water as the cooling fluid as opposed to air.

During one of the simulated flight cycles, an IP radial probe (D2424E), started to cross talk with two of the HP radial probes giving high noise levels. On investigation, the problem was traced to a faulty earthed cable screen in the connector on top of the measuring probe. Re-soldering of the connection eliminated the interference.

Although probe reliability problems still affected the axial movements, the radial fm capacitance probes functioned well throughout. Following the end of the tip clearance measurement section of the test schedule, the IP radial and axial movement measuring probes were removed from the engine and the holes blanked. The HP radial and axial probes remained in the engine for a further 59 hours of engine testing before the engine was

finally stripped and the probes removed. All the radial measuring probes were fully operational at this time.

7.6.0 Discussion of Results.

As with the testing of the fm capacitance tip clearance measuring probes on the engine HP compressor, the quantity of data recorded was considerable. For the purposes of this thesis, presentation of all this data is not relevant and is reported in detail in various internal Rolls-Royce reports. (Refs. 34,35,36 and 37).

7.6.1 Transient Radial Clearance.

Typical plots of the radial clearance probe measurements are shown in Figure 7.16 for the HP turbine and in Figure 7.17 for the IP turbine. These results are as measured during the engine testing and are uncorrected for any axial movements of the HP and IP turbines respectively.

During the acceleration of the engine to a stabilised maximum condition, the turbine radial tip clearances decrease very rapidly due to the cf growth of the blades and disc which comprise the rotor. The turbine casings then begin to heat up and increase in diameter at a faster rate than the turbine discs, so causing a temporary increase in clearance followed by a decrease to its stabilised condition.

Deceleration of the engine results in the opposite effects. Removal of the cf loading causes a rapid increase in clearance

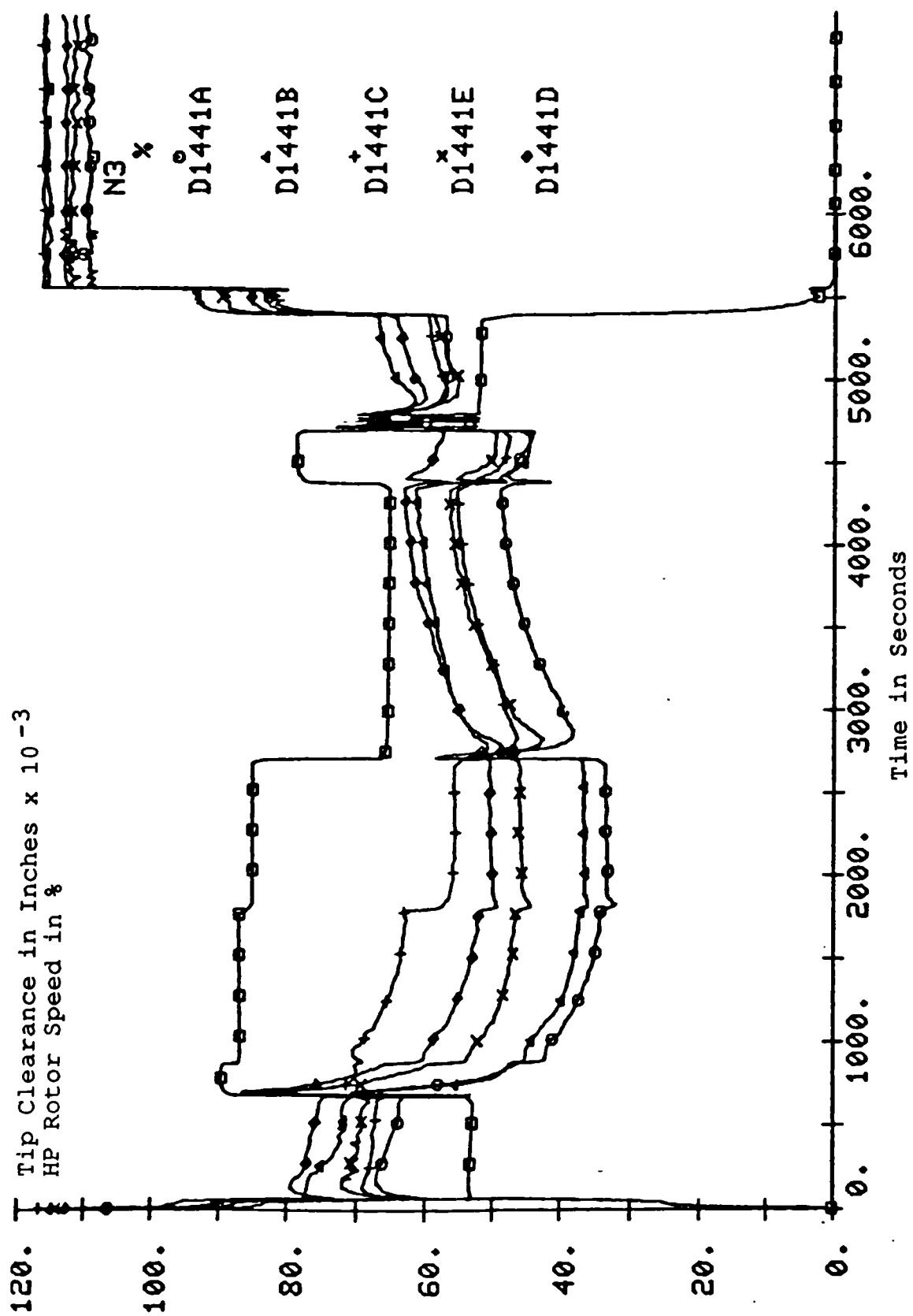


Figure 7.16 HP Turbine Tip Clearance Measurements for Flight Cycle.

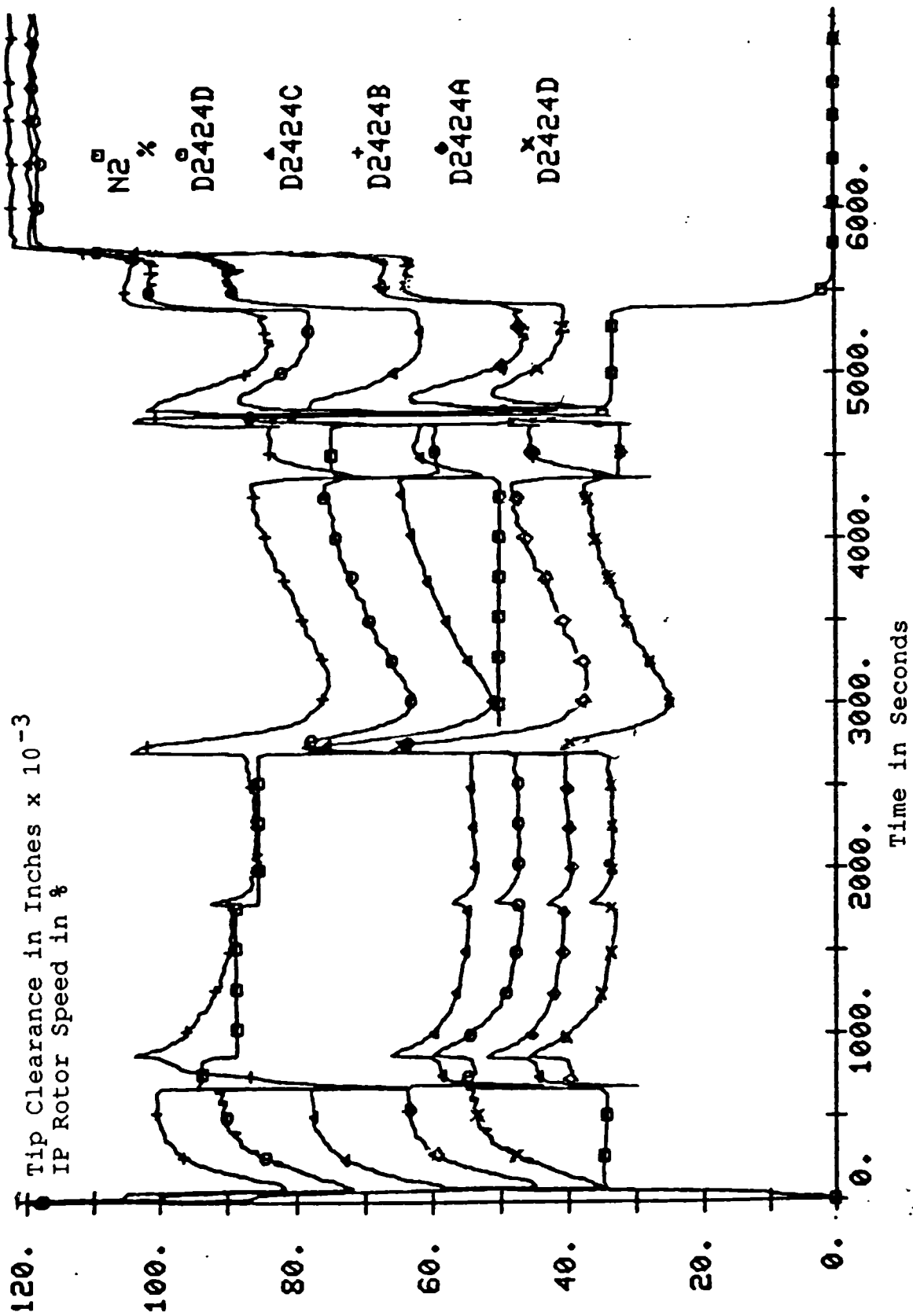


Figure 7.17 IP Turbine Tip Clearance Measurements for Flight Cycle.

as the blades and discs relax. The turbine casings having a lower thermal mass than the turbine discs cool more quickly than the discs causing a decrease in clearance followed by an increase back to the stabilised condition.

Both the HP and IP turbine transient radial tip clearance measurements agreed in their general behaviour very closely with the predictions. The turbine measurements also appeared very similar in character to the transient radial tip clearances measured in the HP compressor and reported in Chapter 6.0. However, when the similarities in the mechanical design of the turbines and compressor are fully appreciated (they are both axial flow turbomachines with blades, discs, casings, similar relative thermal time constants etc.), the similarity in transient tip clearance behaviour is only to be expected.

7.6.2 Casing Eccentricity.

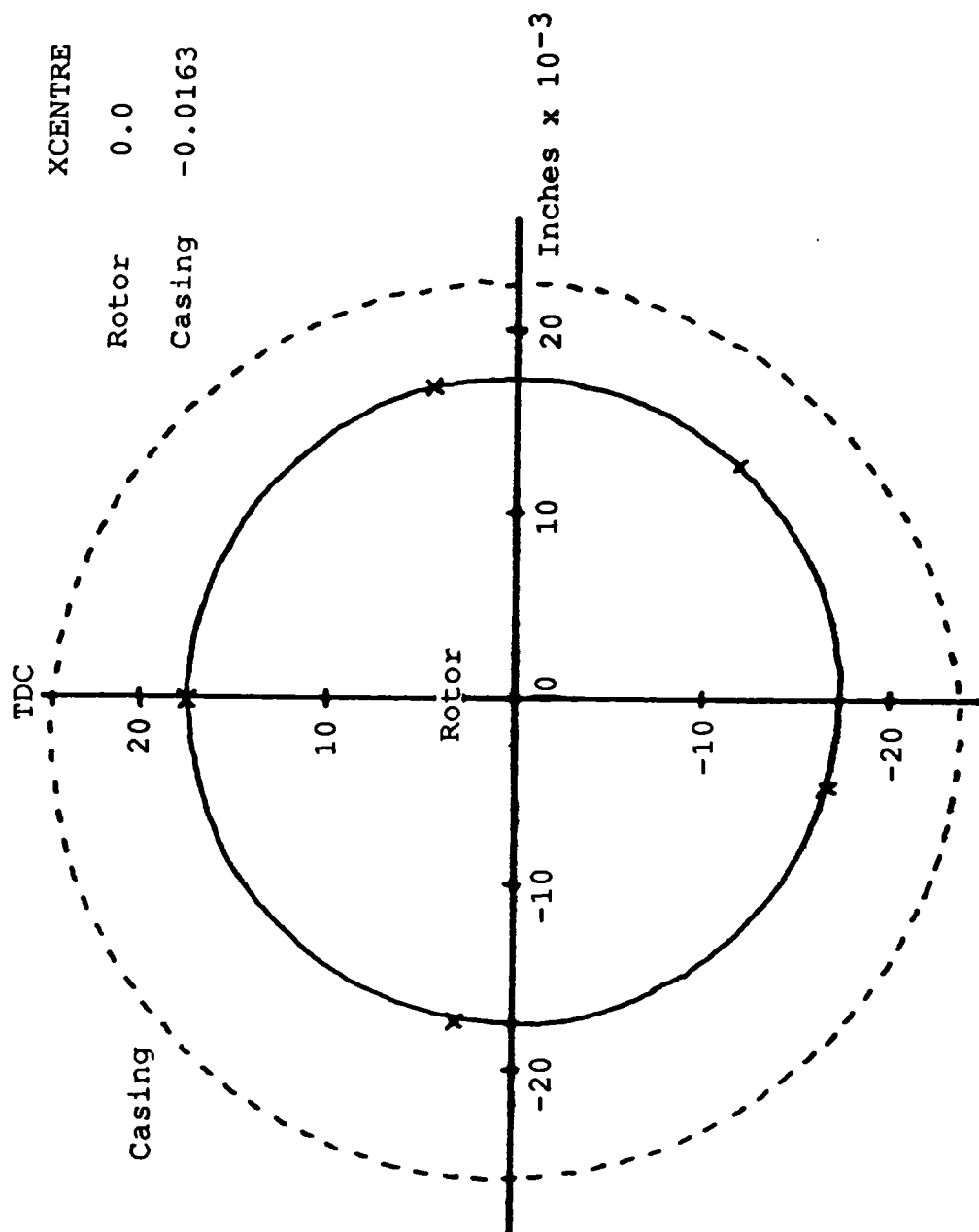
The HP and IP turbine radial tip clearance data was also analysed to show how the eccentricity of the rotors in the casings varied with time and engine condition and obtain a measure of the degree of casing roundness. A computer programme was used to obtain circle fits from the probe data. The rotor was used as a datum, the programme then fitting the best circle through the shroud positions as indicated by the tip clearance probes. To illustrate the analysis process, for each HP turbine radial probe reading, the programme calculated the distance between the centre of the shroud circle to that of the rotor vertically (YCENTRE), horizontally (XCENTRE),

directly (RCENTRE) and the angle subtended, relative to the horizontal port position, between the centres (TCENTRE). Also calculated was the radius of the shroud circle (RADIUS) and a measure of the circle fit (RMS). This is illustrated in Figure 7.18. An example of the plotted data is shown in Figure 7.19 which relates to the HP turbine radial clearance readings during a cold crank of the engine.

The eccentricity plots indicated that at the end of an acceleration to MTO, the rotor is very concentric with the shroud. The end of the acceleration is also the most likely point at which rubs between the blade tips and shrouds may occur, particularly with a hot engine. An even rub pattern over 360 degrees of the casing would thus be expected and in fact agrees well with rub evidence obtained from development engines after testing and strip.

The necessity to correct the radial tip clearance data for axial movements created difficulties in both analysis and interpretation and reduced the overall accuracy of the measurement. It is strongly recommended that for any future tests where tip clearance measurements are required, the fences on the turbine blade tips should be designed to have a zero hade angle, thus removing the dependency of the tip clearances on the measurement of the axial movements.

View from Front



	XCENTRE	YCENTRE	RADIUS
Rotor	0.0	0.0	17.3860
Casing	-0.0163	0.0054	17.4537

Figure 7.19 Plot of HP Turbine Casing Eccentricity.

8.0 CONCLUSIONS.

8.1.0 Summary of the Research.

In Chapter 1 of this thesis, a specification was derived for the measurement of turbine and compressor blade tip clearances in a axial flow gas turbine engine environment. Following a review of previous work in the field of blade tip clearance measurement, it was concluded that no system was currently available which would fully meet the specification. A guarded electrode frequency modulated capacitance technique was subsequently proposed. This choice was based on a theoretical consideration of the peculiar measurement problems encountered above the tips of blades in a gas turbine and the author's practical knowledge and experience of measuring systems in routine use for the research and development of modern turbomachinery.

The capacitance f.m. system was designed, developed and evaluated both in the laboratory and on two gas turbine engines. The data collected during the testing of the measurement technique on the gas turbines at Derby was of particular importance to Rolls-Royce. This was due to the fact that it represented the first occasion on which experimental transient engine blade tip clearance information had been made available. It is also believed that the quantity and quality of tip clearance data obtained during the engine testing of the compressor and turbine, demonstrated a significant advance both in experimental measurement techniques and the understanding of the transient behaviour of the mechanical

structures.

The validation of the tip clearance measurements generated by the capacitance f.m. system proved to be difficult as, at the time of the evaluation, there was no reliable alternative tip clearance measurement technique available against which the results could be compared. However, by means of laboratory simulations, careful comparison of engine build drop-check clearances with measured clearances, comparison of casing rub patterns, visible on engine strip, with zero clearance indications during engine testing and comparison of measured clearances with model predictions, it was possible to validate the measurement technique. The performance of the capacitance f.m. tip clearance measuring system was proved to have either equalled or bettered the original requirement specification in all cases. The capacitance clearance system has subsequently been adopted by Rolls-Royce as the standard technique for the measurement of blade tip clearance in compressors and is used preferentially in turbines where the blade tip geometry is suitable. The system has proved to be relatively inexpensive to manufacture and operate, particularly in comparison with some of the laser based optical measurement techniques, and is easily operated and maintained by the Test Operations Group. Use of the capacitance measurement technique on the two gas turbine engines, as described in Chapters 6 and 7, has yielded the following benefits :-

- * Confirmation at a high level of the structural models used for the design of compressors and turbines. Some details, particularly those relating to the thermal time

constants of casings, blades and discs, have been modified as a direct result of the availability of experimental transient tip clearance measurements.

* A full understanding was obtained of the differences between the surge-prone and the surge-free designs of engine compressor casings. This knowledge should assist the design in the future of more advanced compressors without an inadvertent loss of surge margin due to excessive tip clearances.

* The pass-off test schedule for new production engines and engines after overhaul, which may involve several hot re-slam accelerations, has been modified in the light of the tip clearance data. This is to avoid unnecessary wear to blade tip seals, which may result in engines being delivered to customers with higher specific fuel consumptions than necessary.

Subsequent to the completion of the design, development and evaluation of the tip clearance measuring system, the entire design has been licensed to two companies, Meclec and Rotadata, for commercial exploitation. To date, the royalty and other payments received by Rolls-Royce from the two licensees have only covered an estimated quarter of the cost of development of the measurement technique, excluding the costs associated with the building and testing of the two engines. A full cost benefit analysis of the measurement technique is very difficult to perform due to the inability to quantify accurately, in monetary terms, the advantages of possessing particular engineering data. However, based on the assumption that the experimental blade tip clearance data

collected during the evaluation of the measurement technique will enable only one future design of compressor casing to avoid the surge problems previously experienced, the programme of research will have paid for itself at least ten times over.

8.2.0 Proposals for Further Work.

8.2.1 Guard Circuit Amplifier.

The most restricting characteristic of the of the capacitance f.m. clearance system has been found to be the inability of the guard circuit amplifier in the measuring probe modulator to drive effectively a reactive load of greater than 180 picofarads (Chapter 4.2.4). This has resulted in a maximum possible separation of only 180 mm between the sensor and modulator in the measuring probe, when using high temperature minerally insulated cable. The potential for application of the measurement technique would be considerably enhanced, and existing applications made easier, if this dimension could be increased. Although it is believed that some scope exists for replacing the currently used double screened alumina insulated cable with one of a lower capacitance, the most profitable approach is considered to involve a redesign of the guard circuit amplifier to have a greater drive capability. The use of a phase advance network at the input to the amplifier could prove beneficial.

8.2.2 System Calibration.

Due to the variation in characteristics of both the measuring

probes and the demodulators, each measuring probe is calibrated with a specific demodulator unit as a pair. This feature imposes operational restrictions in that interchangeability of probes and demodulators can only be achieved by recalibration. A means of achieving true interchangeability has been proposed by D.R.Foulds at Rolls-Royce whereby an end-to-end system calibration factor is derived from injecting a reference a.c. signal on the modulator a.f.c. voltage. The viability of this innovation is currently under investigation.

8.2.3 Measuring Probe-Sensor.

The design of the measuring probe for use in the engine turbine relied on an external supply of high pressure air to keep the sensor sufficiently cool such that the braze between the ceramic and metal components maintained the integrity of the assembly. A design of sensor which could function reliably at a temperature close to that of the turbine gases without the need for cooling would be a significant operational advantage. If the capacitance technique were to be considered for a production engine application as part of a closed loop tip clearance control system, the use of externally supplied cooling air would not be possible and the availability of engine supplied cooling air would be severely restricted. A sensor design, using hot pressed silicon nitride as the insulating material and sputtered thin film platinum electrodes, has been proposed and will be evaluated.

9.0 REFERENCES.

1. Freeman, C.

"Effect of tip clearance flow on compressor stability and engine performance."

Von Karman Institute for Fluid Dynamics. Lecture series
1985-05 Tip clearance effects in axial turbomachines.

2. Drinkuth, W., Alwang, W.G., House, R.

"Laser proximity probes for the measurement of turbine blade running clearances."

I.S.A. A.S.I. 74228, 1974.

3. Ford, M.J.

"Clearance measurement system."

N.A.S.A. CR 159402

4. Barranger, J.P., Ford, M.J.

"Laser-optical blade tip clearance measurement system."

A.S.M.E. Gas Turbine Conference 1980 New Orleans, U.S.A.

5. Hardy, H.D.

"Use of laser-powered optical proximity probe in advanced turbofan engine development."

Symposium on Airbreathing Propulsion, Sept. 1972, Progress in
Astronautics and Aeronautics Vol. 34

6. White, Steven D.

"Turbine tip clearance measurement"

USARTL-TR-77-47.

7. Baker, L.C., Grady, G.E., Mauch, H.R.

"Turbine tip clearance measurement"

USARTL-TR-78-4.

8. Amsbury, C.R., Chivers, J.W.H.

"System for the measurement of rotor tip clearance and displacement in a gas turbine."

AGARD Conference Proceedings, Seal Technology in Gas Turbine Engines, No.234, 1978.

9. Davidson, D.P., De Rose, Winnerstrom.

"Measurement of Turbomachinery Stator to Drum Running Clearances."

ASME Gas Turbine Conference, 1983, Phoenix, Ar., USA
83-GT-204.

10. Knoell, H., Schedl, K., Kappler, G.

"Two Advanced Measuring Techniques for the determination of rotor tip clearance during transient operation."

Fifth International Symposium on Airbreathing Engines, 1981, Bangalore, India.

11. Belsterling, C.A.

"Sensing with Air."

25th. ISA Conference , 1970, Philadelphia, USA.

12. Hall, L.C., Jones, B.E.

"An investigation into the use of a cone-jet sensor for clearance and eccentricity measurement in turbo machinery."

Proceedings of the Institution of Mechanical Engineers, Volume
190, 17/76

13. Rubinshtein, Ya.M., Trubilov, M.A.

"A steamjet method for measuring clearance in steam turbines."
Teploenergetika 1958, 68-74.

14. Barranger, J.

"An in-place recalibration technique to extend the temperature
capability of capacitance-sensing rotor blade tip clearance
measuring systems."

SAE 781003, 1978 Aerospace Meeting, San Diego, USA.

15. Poppel, G.L.

"Analysis and preliminary design of an optical digital tip
clearance sensor for propulsion control."

NASA-CR-159434.

16. Besant, C.B., Wright, T.C.F.

"A measurement system for active tip clearance control."

Internal Report, Aug. 1982, Dept. of Mechanical Engineering,
Imperial College, London.

17. Kaye, G.W.C., Labey, T.H.

"Tables of Physical and Chemical Constants."

Longman.

18. Hague, B.,

"Alternating Bridge Methods."

Pitman, London. (1946)

19. Thomas, H.E. and Clarke, C.A. (ed.)
"Handbook of Electrical Instruments and Measuring Techniques."
Prentice Hall, Englewood Cliffs, New Jersey. (1967)
20. Helke, H.,
"Messbrücken und Kompensationen für Wechselstrom."
Oldenbourg, Munich. (1971)
21. Walsh, R.,
"Inductance Ratio Arms in Alternating Current Bridge
Circuits."
Phil. Mag. 10, 49-70 (1930)
22. Starr, A.T.,
"A Note on Impedance Measurement."
Wireless Engineer, exp. Wireless 9, 615-617 (1932)
23. Clark, H.A.M. and Vanderlyn, P.B.,
"Double Ratio a.c. Bridges with Inductively Coupled Ratio
Arms."
Proc. Inst. Elect. Engineers, 96, 365. (1949)
24. Neubert, Harman K.P.,
"Instrument Transducers."
Oxford University Press (1975)
25. Hardy, James K.,
"High Frequency Circuit Design."
Reston Publishing Company Inc.

26. Ristenbatt, Marlin P., Riddle, Robett L.,
"Transistor Physics and Circuits."
Prentice-Hall Inc.

27." The Radio Communications Handbook."
The Radio Society of Great Britain.

28." The Radio Amateur's Handbook."
The American Radio Relay League.

29. Comer, David J.,
"Modern Electronic Circuit Design."
Addison-Wesley Publishing Company.

30. Hawkins, M.J.,
"Results of Analysis of HP Compressor Tip Clearances Stages 2
and 5."
Rolls-Royce Internal Report.

31. Hawkins, M.J.,
"Analysis and Comparison of HP Compressor Tip Clearance
Measurements."
Rolls-Royce Internal Report.

32. Sadler, J.,
"Analysis of HP Compressor Casing Temperatures and Deduction
of Stage 4, 5 and 6 Tip Clearances."
Rolls-Royce Internal Report.

33. Edmondson, W.D.,

"Comparison of Tip Clearances of an Advanced Engineering HP Compressor with the Basic Existing Design of Casing."

Rolls-Royce Internal Report.

34. Simkin, P.,

"HP Turbine Tip Axial and Radial Movement Data Corrections."

Rolls-Royce Internal Report.

35. Simkin, P.,

"Analysis of HP Turbine Tip Clearance Test Results."

Rolls-Royce Internal Report.

36. Allum, D.M.,

"IP Turbine Tip Axial and Radial Movement Data Correction."

Rolls-Royce Internal Report.

37. Hill, R.A.,

"HP/IP Turbine Tip Clearance Tests-Parts 1, 2 and 3."

Rolls-Royce Internal Report.

38. Data Sheet on XR-215 Monolithic Phase-Locked Loop by Exar Integrated Systems Inc., 773, North Pastoria Avenue, Sunnyvale, California, 94086, USA.